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Preface

Since 1975, the Systems Analysis Working Group of the Society of American Foresters has sponsored seven symposia to highlight advancements in quantitative approaches to solve forest resource problems. Past symposia were held in Athens, GA (1975 and 1985), Asilomar, CA (1988 and 1994), Charleston, SC (1991), Valdivia, Chile (1993). This proceedings reports on the seventh symposium, held in Traverse City, MI, in 1997. The eighth conference will be held in Aspen, CO, in 2000.

Seventy-one of the papers and posters offered at the 1997 Seventh Symposium on Systems Analysis in Forest Resources are contained in these proceedings. The conference setting, Shanty Creek Resort, provided a relaxed setting for the 125 participants from many countries. Captain Chuck Sipe, the plenary speaker from the U.S. Naval War College, presented a challenging view of decision-making in his talk "The Decision-Maker Analyst Nexus." Dinner speaker Professor Paul Nickel, from the Department of Resource Development at Michigan State University, chided the modeling community with his remarks on the "Care, Feeding and Destruction of Handsome Models." Symposia presentations covered an extraordinary range of topics offered by participants from more than a dozen countries. Topics included management objectives and operations, information systems, transportation models, optimization and simulation methods, decision support techniques, spatial analyses, timber supply, regional economics, disturbances, and management of landscapes, wildlife, and biodiversity.

Many organizations and individuals contributed to the success of this symposium. We greatly appreciate support from the primary organizational sponsors—the Society of American Foresters, Michigan State University, and the North Central Research Station of the USDA Forest Service.

The unending details associated with planning and organizing a major conference required considerable effort by many people; we gratefully salute their contributions. Gem Castillo, Brad Conway, Demetrios Gatziolis, and Barbara Anderson from the Department of Forestry at Michigan State University and Kathleen Tully provided logistics and program support. Professor Keith Gilless, from the University of California, pitched in on session scheduling and program production. Assistance in editing and preparing the proceedings was provided by Ariana Mikulski, Sara Panek, Barbara Winters, Mary Peterson, and Lucy Burde from the North Central Research Station. The conference and these proceedings would not have been possible without the substantial efforts of these people.

Manuscript authors are responsible for the accuracy of their papers. While not peer reviewed, the papers contained in this volume have been carefully reviewed and edited for completeness and consistent format. The mention of trade names within the papers does not constitute an endorsement by the U.S. Department of Agriculture or any of the sponsors of this symposium. Thanks to all of the authors who contributed to this volume for their efforts and patience. We look forward to seeing you in Aspen in September 2000.

Jeremy Fried, Larry Leefers, and Mike Vasievich
Program Committee

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Seventh Symposium on Systems Analysis in Forest Resources

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APPLYING SIMULATION AND OPTIMIZATION TO ADDRESS FOREST HEALTH ISSUES AT LANDSCAPE SCALES

Hans R. Zuuring, J. Greg Jones, and Jimmie D. Chew[1]

ABSTRACT.—SIMPPLLE (**SIM**ulating Vegetative **P**atterns and **P**rocesses at **L**andscape Sca**LE**s) is a stochastic simulation model for projecting vegetative change over time in the presence of natural processes, either with or without management treatments. The interaction of various natural processes on a landscape are modeled, making it a powerful tool for assessing forest health in time and space. MAGIS (**M**ulti-resource **A**nalysis and **G**eographic **I**nformation **S**ystem) is an optimization modeling system for integrating ecological and social information and scheduling management practices spatially and temporally for a landscape. A wide variety of land management practices can be accommodated and a transportation component is available for trails and roads. Various management relationships can be developed for issues applied to an entire planning area, or geographic subcomponents. We present an approach for addressing forest health in a landscape planning context which takes advantage of the strengths of both modeling approaches. SIMPPLLE is used to assess health risks on the current landscape due to the interaction of various natural processes. MAGIS is then employed to schedule management activities which reduce these risks, as well as address other management objectives present for the area.

INTRODUCTION

The modeling framework presented in this paper is one product of a collaboration between scientists and land managers working on the Landscape Analysis Group of the Bitterroot Ecosystem Management/Research Project (BEMRP), a project which was initiated in October 1994 (Carlson *et al.* 1996). The goals of BEMRP were to predict landscape level influences of vegetation management on multiple resource outputs and values in an altered Rocky Mountain ecosystem, and to demonstrate to the public the feasibility of landscape-level rehabilitation management. The specific objective was to address the effects of landscape-level vegetation management: (1) on wildfire hazard at the wildland/urban interface; (2) on a major esthetic resource; (3) on quantity and quality of timber resources; (4) on wildlife, including elk, deer, small mammals, and birds; (5) on economics and social implications of ecosystem management; and (6) on restoring health in low and high elevation forests.

Through close cooperation and collaboration with the Bitterroot National Forest, the University of Montana, and the Rocky Mountain Research Station considerable progress has been made towards achieving the above objectives. Specifically, a GIS database has been completed for the 58,083-acre Stevensville West Central (SWC) Integrated Resource Analysis unit. Two modeling systems, SIMPPLLE (**SIM**ulating Vegetative **P**atterns and **P**rocesses at **L**andscape Sca**LE**s) and MAGIS (**M**ulti-Resource **A**nalysis and **G**eographic **I**nformation **S**ystem) have been developed to interact with the GIS database. SIMPPLLE is a model that projects changes in vegetation over time and space using a state/pathway approach (Chew 1995). A vegetative state is defined by dominant tree species, size class, and density as well as an association with a habitat type group (Pfister *et al.* 1977). MAGIS is a microcomputer-based spatial decision support system (SDSS) for planning land management and transportation-related activities on a geographic and temporal basis in the presence of multiple and sometimes conflicting objectives (Zuuring *et al.* 1995). These models permit land managers: (1) to predict vegetation change over landscapes, (2) to predict change in the probability of disturbance processes relative to vegetation change, and (3) to predict future effects on resource values.

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THE PROBLEM

Land managers are interested in projecting vegetation into the future while accounting for the presence of various natural processes such as fire, mountain pine beetle, spruce budworm, and root rot at landscape scales for project planning purposes. Specifically they want to estimate and compare the effects of various management alternatives against the 'no action' alternative. Forest health, however, is but one of many issues of concern to land managers. Ultimately management activities must be planned and implemented in view of a variety of objectives and constraints that arise from the Forest Plan and scoping done by Forest resource specialists and the public. Managers must be able to develop and evaluate alternatives that address the sometimes conflicting objectives and constraints. This assessment of alternatives and the implementation of the selected alternative is carried out in a spatial context at the landscape level. Models like SIMPPLLE and MAGIS serve as useful tools for addressing forest health problems but great care must be taken to properly formulate the planning problem.

With regard to forest health, a workable definition and an objective means of quantifying it are needed. The term "forest health" suffers from a plurality of definitions thus making it a fuzzy phrase. Our definition of forest health deals with a situation in which natural processes and ecosystem functions are allowed to operate at a landscape level. A proxy for forest health is a risk rating which is associated with pathological and entomological agents operating at the stand level. The question is how can such a rating be computed and what sort of modeling system is needed to determine a schedule of management activities applied over time and space that minimizes such risks at landscape sales.

THE SOLUTION

Although the above problem has been addressed by some analysts using a single modeling system approach, we have chosen to utilize two landscape modeling systems that are integrated for project planning purposes. A simulator and an optimizer are employed and executed as separate entities that share information, allowing the analyst to utilize the strengths of both modeling systems (fig. 1).

The process begins by using SIMPPLLE to project the frequency and location of natural disturbances for the "no action" management alternative with fire suppression. These results are then utilized to compute a risk index for each stand, based on the most likely type of disturbance and the probability of its occurrence. This index is incorporated into a management relation, built in MAGIS, to address forest health issues. Other issues are

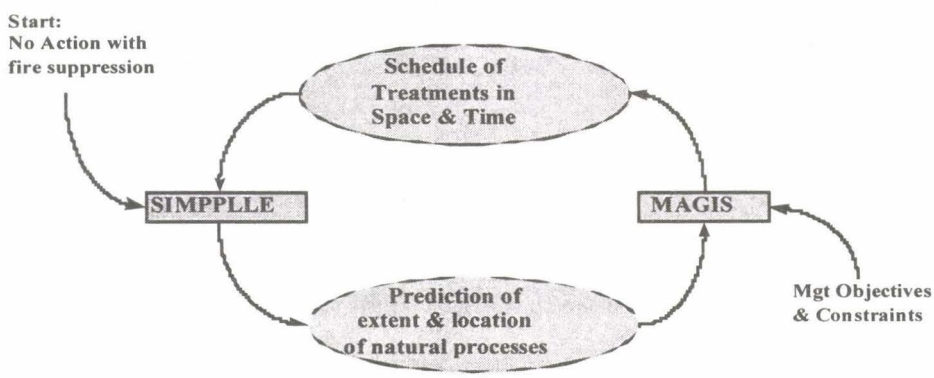

Figure 1.—*Analysis approach flowchart.*

handled by additional management relations that together comprise a planning scenario. Examples of such relations are: (1) acres in various stand size classes, (2) equivalent clear cut acres by watershed, (3) sediment production by watershed, (4) big game hiding cover by third order drainage, (5) pine marten habitat index by third order drainage, and (6) net revenues from several accounting stances. Amounts are calculated for these management relations when MAGIS is run in either ***simulation mode*** (managers choose the location and timing of activities) or ***optimization mode*** (the solution process chooses the timing and location of activities based on the stated objectives). In a forest health situation the analyst is usually interested in *minimizing* a risk index subject to a set of constraining management relations while attaining a reasonable net revenue (not maximized but costs are at least covered by revenues). The solution yields outputs in the form of stand acres that are multiplied by their corresponding risk index and summed over all stands. In this manner, a number of alternative planning scenarios, each consisting of a series of treatments applied over time and space, can be compared (based on certain criteria) to identify those alternatives that reduce or eliminate the risk. The schedule of activities proposed by MAGIS is imported into SIMPPLLE where additional simulations are run to evaluate the changes in location and extent of disturbances associated with these activities.

AN APPLICATION

A landscape planning process has been undertaken on the Stevensville West Central area of the Bitterroot National Forest that addresses 10 issues:

1. Pine marten habitat index by third-order drainage;
2. Pileated woodpecker index by third-order drainage;
3. Old growth (acres) by third-order drainage;
4. Big game habitat characterized by hiding and thermal cover (acres) by third-order drainage;
5. Watershed impacts characterized by sediment, water yield, and equivalent cut acres;
6. Visual quality;
7. Unroaded acres;
8. Economic viability (feasibility);
9. Size class distribution; and
10. Ecosystem restoration characterized by improved forest health and wildlife habitats.

The first step was to run stochastic simulations of SIMPPLLE over five decades for the "no action" management alternative with fire suppression. This permitted land managers to evaluate the current situation because there were concerns about the potential spatial distribution and size of areas disturbed by natural processes, especially fire. The number of acres impacted by three specific natural processes and their associated frequencies of occurrence in stands located across the landscape were computed. These three processes were: (a) stand replacement fire, (b) western spruce budworm, and (c) mountain pine beetle in ponderosa pine. From these results, a risk index was constructed based on the conditions listed in table 1. This risk index is a relative quantity based on an analyst's notion of the desired future condition (DFC) of a landscape and the undesirable effect that these processes have on achieving those desired conditions. For each stand risk, index values were entered into MAGIS, and a risk index management relation was constructed. The next step was to calculate the risk index for the "no action" alternative, and to calculate the effects on the issues incorporated in Alternative 1 developed by forest managers. MAGIS was run in simulation mode to calculate those effects. Alternative 1 would implement various harvest treatments on 4,821 acres with a total harvest volume of 3.6 MMBF, pre-commercial thinning on 1,159 acres and under-burning on 5,206 acres. These treatments were applied on 14,155 acres of non-wilderness USDA Forest Service lands. No treatments were prescribed in the planning process for the 25,283 acres in wilderness and 18,645 acres in private ownership within the SWC unit.

Table 1.—*Risk index values by source and frequency cutoff*

Value	Risk Source	Freq. Cutoff
		percent
0	stand not listed	
2	low prob. stand replacing fire	≥ 20 and < 50
4	high prob. stand replacing fire	≥ 50
6	light spruce budworm	≥ 50
8	mountain pine beetle	≥ 50
10	severe spruce budworm	≥ 50

MAGIS was then run in optimization mode to formulate additional management alternatives which quantified one or more of the 10 issues. These alternatives varied in the manner by which specific issues were addressed. Table 2 presents the specifications for three of the more interesting alternatives developed through MAGIS. Like Alternative 1, treatments were prescribed only for non-wilderness Forest Service lands. Each of the three alternatives restrict harvest volume in each decade to the harvest volume of Alternative 1 in decade 1. Alternatives 3 and 6 were developed by first minimizing the risk index from SIMPPLLE, then achieving a second solution in which PNV was maximized while holding the risk index to the previously attained minimum value.

Table 2.—*Objectives and constraints addressed by three alternative planning scenarios*

Issue	Alt 3	Alt 6	Alt 7
Harvest Vol ≤ Alt 1	X	X	X
Alt 1 Burn & PCT[a]		X	X
Water Disturbance Limits	X		X
Wildlife ≥ Alt 1	X		X
Seed tree & Clearcut = 0	X		X
Risk Index ≤ Alt 1			X
Min Risk/Max PNV[b]	X	X	
Maximize PNV			X

[a] pre-commercial thin
[b] present net value

Table 3 summarizes the results pertaining to the three alternatives mentioned above as well as the "no action" alternative and Alternative 1. Alternative 7 is most like Alternative 1 since it yields the same or improved values for all the quantified issues, with an increase of over $500,000 in overall present net value and $400,000 in decade 1 alone. Alternative 6 shows that additional reductions in the Risk Index are possible, with further improved present net values, but only after relaxing the watershed disturbance limits and wildlife objectives achieved in Alternative 1. Alternative 3 does not include the pre-commercial thinning and under-burning treatments of Alternative 1, but does achieve the lowest risk index of the listed alternatives with the highest present net values.

The "no action" alternative shows a risk index value of 23,956 and zeros for all other decision variables. Alternative 1 which is the one developed by the ID team, indicates a negative PNV of $779,000, a risk index of 20,215 and the largest amount of acres in selection cuts. The most attractive solution appears to be Alternative 3 because present net value (PNV) is positive ($867,000) and the Risk Index is the lowest (14,900). Both Alternative 6 and 7 indicate the highest number of acres receiving under-burning and it appears that the increased harvesting in periods two and three occurring with Alternative 6 over that of Alternative 7 yields a positive PNV of $664,000 and the second lowest Risk Index of 15,247.

Finally the above four management alternatives were entered into SIMPPLLE and five simulations were conducted over five decades for each of three natural processes: (a) stand replacing fire, (b) western spruce budworm (WSBW), and (c) mountain pine beetle (MPB) in ponderosa pine. The mean sizes of areas (in acres) estimated to be affected by each of the above three natural processes for each of five decades were computed and plotted for the four alternatives and the "no action" alternative in figure 2a-c. The number of acres burned by stand replacement fires over all five decades was similar for all five management alternatives with the exception of alternative 7 which exhibited a decrease in decade 3. All alternatives showed a sharp increase in burned acres by decade 5. With regard to severe WSBW, all alternatives exhibited a sharp decrease in the mean number of acres infected from decade 1 to decade 2, which continued modestly until decade 3, and then slowly increased up to decade 5. The "no action" alternative generally displayed the highest acres infested over all five decades. The mean number of acres infected with MPB in ponderosa pine was highly variable for all alternatives over all five decades with the "no action" alternative exhibiting the highest acreage at decades 2, 3, and 4. Alternative 6 showed a sharp increase in the mean number of acres infected by MPB by decade 5. The number of acres disturbed by both severe WSBW and MPB in ponderosa pine were reduced over time by all four alternatives compared to the "no action" alternative. Further improvements on the 58,000-acre area were hampered by the fact that treatments are possible only on the 14,155 acres of non-wilderness Forest Service lands.

Table 3.—*Summary of solution amounts for selected management relations from four alternatives and the "no action" alternative*

Management relation	Units	NoAct	Alt1	Alt3	Alt6	Alt7
PNV-overall	Thous $	0	-779	867	664	-233
PNV-Decade 1	Thous $	0	-544	531	-27	-142
Risk Index	Index	23,956	20,215	14,900	15,427	20,189
Harvest Vol-Decade 1	MBF	0	3,631	3,600	3,600	3,600
Harvest Vol-Decade 2	MBF	0	0	3,600	3,600	2,220
Harvest Vol-Decade 3	MBF	0	0	3,600	3,600	1,307
Under-burning	Acres	0	5,206	1,011	6,068	6,206
Pre-commercial Thin	Acres	0	1,159	0	1,159	1,159
Sanitation/salvage Cuts	Acres	0	1,288	31	0	130
Commercial Thin	Acres	0	491	386	429	395
Selection Cuts	Acres	0	2,963	844	4	1,134
Regeneration Cuts	Acres	0	79	16	61	80

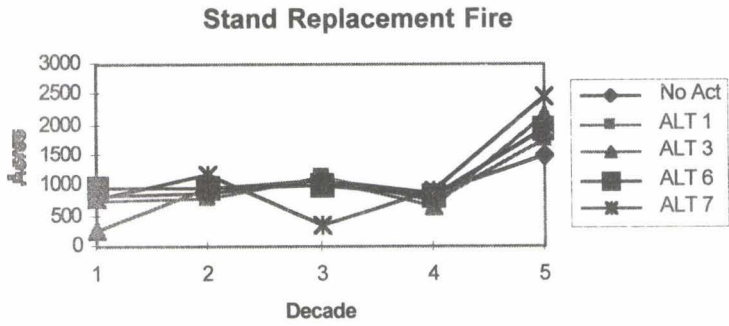

Figure 2a.—*Estimated mean number of acres affected by stand replacement fire over five decades.*

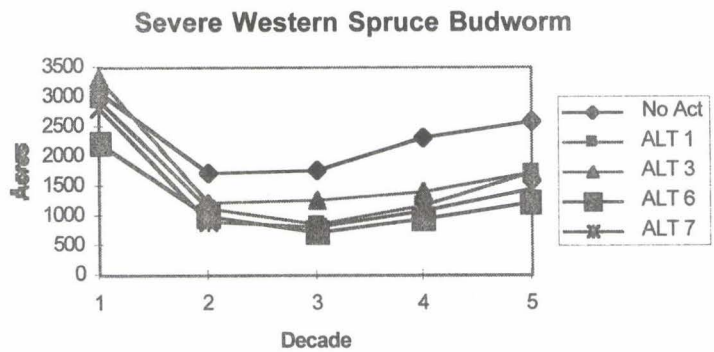

Figure 2b.—*Estimated mean number of acres affected by severe western spruce budworm over five decades.*

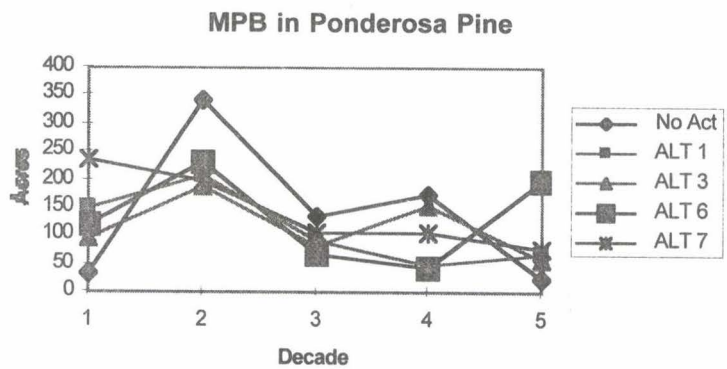

Figure 2c.—*Estimated mean number of acres affected by mountain pine beetle in ponderosa pine over five decades.*

DISCUSSION

This research indicates a potentially big payoff by integrating simulation and optimization models such as SIMPPLLE and MAGIS. First, a simulation model like SIMPPLLE is valuable for predicting vegetative changes under no management and the likely extent and location of various natural processes. The stands at risk can be prioritized and entered into MAGIS, which then chooses the timing and location of activities based on this priority as well as the other objectives associated with issues and concerns. This schedule of activities addresses the health issues to the extent possible while meeting the other environmental and social objectives. The resulting schedule of activities can then be entered into SIMPPLLE and the future can again be simulated in terms of vegetative change and extent of natural processes. This provides a good measure of the effectiveness of the activities in addressing forest health issues and in creating the desired future stands. Through the utilization of new tools such as GIS, SIMPPLLE, and MAGIS, that support ecosystem management and landscape analyses, the ability to better under-stand, manage, and monitor Bitterroot and Northern Rocky Mountain ecosystems is becoming a reality.

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A HIERARCHICAL APPROACH TO SPATIAL FOREST PLANNING

Ugo Feunekes and Andrew Cogswell[1]

ABSTRACT. —This paper describes a hierarchical approach to spatial forest planning developed by Remsoft that can be used to create harvest blocks that meet maximum opening, green-up, and other constraints. The approach relies heavily on decisions and trade-offs made during long-term strategic analysis to simplify the blocking phase and to ensure that the harvest blocks generated meet long-term objectives and constraints. A series of case studies illustrates the implementation of the system on the ground and highlights key components of the approach.

INTRODUCTION

The practice of forestry is increasingly coming under the regulatory influence of many different organizations, from environmental watchdogs to Federal agencies (e.g., NEPA). Concerns over the impacts of forest operations on the forest landscape have compelled a number of agencies to take initiatives to address these issues. One result of this has been the definition of explicit limits on how forest operations should be implemented and the establishment of procedures to measure compliance with these guidelines. The American Forest & Paper Association, for example, has taken a proactive approach by outlining guidelines for member forest companies to implement sustainable forestry practices (Wallinger 1995), many of which represent a fundamental change in how forest planning and operations are practiced. In addition, many of these guidelines have a significant impact on both present and future harvest volumes.

At the same time, forest management planning, particularly harvest scheduling under spatial constraints, has witnessed notable advances in the techniques and approaches used to solve the problem. Nevertheless, practical, comprehensive procedures and tools that aid forest managers in developing sustainable, spatially feasible management plans at an operational-scale are still rare. This is because the majority of techniques cannot deal with problems on the scale faced by forest managers—typically hundreds of thousands of polygons. Also, issues surrounding the actual implementation of a planning system have not yet been adequately addressed.

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This paper describes an approach developed by Remsoft and used by a number of forest companies throughout North America to produce spatially feasible harvest schedules that meet long-term sustainability criteria. The approach has been shown to work on both small case studies as well as operational-sized problems.

BACKGROUND

Spatial planning problems are especially difficult to solve for three reasons. First, most scheduling problems involve large numbers of stands and/or harvest blocks. Sheer size limits the techniques that can be effectively applied to the problem. Second, a long-term look is required to address sustainability—usually several rotations. As planning horizons increase, the decision variables and constraints necessary to represent adjacencies increase exponentially. Finally, spatial allocation and scheduling in the second-growth forest is often dubious because of the uncertainty in regeneration responses. When all of these factors are considered together, it is clear that finding a true optimal solution to an unrestricted problem is virtually impossible. As a result, every spatial planning approach has focused on finding good or near-optimal, feasible solutions, but on simplified problems.

A number of different techniques have been employed to solve spatially-constrained harvest scheduling problems. These include various mixed-integer programming formulations (Meneghin *et al.* 1988, Jones *et al.* 1991, Weintraub *et al.* 1994, Yoshimoto *et al.* 1994), binary search or inventory projection models (Baskent 1990), simulated annealing (Moore and Lockwood 1990), and Monte Carlo integer programming (MCIP) (O'Hara *et al.* 1989, Clements *et al.* 1990), to name a few.

The size of the problem that can feasibly be addressed and the high cost of finding solutions limit purely mathematical programming techniques (Weintraub *et al.* 1995). To be solvable in this manner, the problem must be simplified, usually by limiting the planning horizon (Nelson and Brodie 1990), constraint set, or the number of harvest units. Others have combined optimization techniques and heuristics to find very good, near-optimal solutions to spatial planning problems (Yoshimoto *et al.* 1994, Clements *et al.* 1990, Weintraub *et al.* 1995). However, none of these approaches have been demonstrated to work for problems on an operational scale.

Simulated annealing has several potential advantages over mixed-integer programming, including the ability to model a large number of stands. Given sufficient computational effort, simulated annealing models will theoretically converge to an optimal solution, although the time to convergence may be excessive. Moore and Lockwood (1990) used simulated annealing for a problem with a large number of stands where each stand could only be considered for one treatment over the planning horizon. However, regenerated stands were not considered, thus limiting the process to long-term sustainability issues.

Baskent (1990) used an inventory projection model in combination with an aggregation heuristic to solve large-size spatial scheduling problems over the long-term. While simulation circumvents the problem size limit inherent in purely mathematical programming techniques, the inability to balance multiple product flows is a major drawback. Moreover, any approach that schedules the harvest sequentially is susceptible to future infeasibilities as the number of options is reduced over time (Brodie and Sessions 1991, Remsoft 1996).

Others have tried to solve the spatial scheduling problems in two steps, separating the problem based on the amount of time and spatial detail considered. Nelson *et al.* (1991) use such a hierarchical approach to develop spatially feasible harvest schedules. First, a stratum-based linear programming (LP) approach is used to solve the long-term scheduling problem subject to forest-wide constraints but without specific spatial detail. Then, in a separate step, the cut is allocated to blocks for the first few periods of the long-term planning horizon and scheduled using a MCIP model. Beyond the problem of manually delineating blocks, the difficulty with this approach is that the only explicit linkage between the strategic and tactical planning models is the allowable harvest. Thus, the tactical solution may be incompatible with more long-term goals.

Jamnick and Walters (1991) also used a hierarchical approach in which the problem was solved in two distinct phases. The first was a strategic planning phase in which long-term (two or more rotations), nonspatial objectives and constraints were evaluated using traditional LP techniques. Stand-level spatial resolution was not considered in this phase. The second phase was a spatial planning phase where harvest activities were scheduled subject to adjacency delay, opening size, and harvest flow constraints over a much shorter time frame (one rotation). What differentiates this approach from others is that the two phases are closely linked by the harvest timings and stand types chosen in the strategic phase (Cogswell 1995). In addition, an automated harvest block generator (Walters 1991) was used, eliminating the need to manually delineate blocks prior to the spatial phase.

REMSOFT'S SPATIAL PLANNING SYSTEM

For a number of years, Remsoft has been refining and adapting the Jamnick and Walters approach, building on its inherent strengths, addressing its weaknesses, and turning the approach into an implementable spatial planning system. Our design criteria included the following: the system had to (1) be flexible to allow it to operate in different jurisdictions; (2) be scalable; that is, it should work on small problems as well as operational-sized problems containing hundreds of thousands of polygons; (3) be theoretically sound in terms of ensuring that long-term outlooks are not ignored; (4) make reasonable demands in terms of hardware, time to solution, and other system requirements; and finally, (5) provide reasonable, near-optimal solutions.

As the system was refined and tested (Walters and Feunekes 1994, Cogswell 1995), one key strength became evident: since most of the problem is solved in the strategic, nonspatial phase, the spatial problem has been sufficiently simplified to allow our design criteria to be met. By using the results of the first phase as the starting point and attempting to implement the strategic harvest schedule, the spatial phase inherits all of the outcomes of the strategic analysis without explicitly recognizing the individual constraints. Short- and long-term trade-offs among silvicultural levels, habitat levels, spatial trade-offs, product flows, etc., have already been evaluated and optimized and are accounted for in the harvest schedule.

For example, in a strategic model it may be determined that to produce an optimal flow of a certain product, one should harvest 1,000 acres of 40-year-old pine in year five, followed by an additional 500 acres in year six. It is irrelevant to the strategic model that there are in fact 12 forest stands within the 1,500 acres of scheduled area, or which of the 12 are harvested in year five versus year six. All that is relevant is that 1,000 acres is cut in year five followed by 500 acres the following year. If this occurs, then the objectives and constraints will be satisfied.

In the spatial phase, the problem therefore becomes one of determining which of the 12 stands should be harvested in year five and which should be harvested in year six. At this stage, it is irrelevant why 1,000 acres should be harvested in year five and 500 in year six. Furthermore, if stands in the spatial phase are scheduled to match the optimal timings determined in the strategic phase, all of the constraints from the strategic phase will be met.

The spatial planning system developed by Remsoft includes a forest modeling system; Woodstock (Walters 1993), a harvest block allocation and scheduling tool; Stanley (Remsoft 1996), a tool for forest-stand allocation; and a collection of utilities to generate the required spatial data and view the resulting harvest blocks. Woodstock generates LP matrices using a generalized Model II formulation and produces optimal solutions for the long-term, strategic portion of the harvest scheduling problem. Using the harvest schedule from Woodstock, Stanley allocates forest stands to harvest blocks subject to adjacency, maximum opening size, and harvest flow constraints.

CASE STUDIES

We present three different case studies to demonstrate how the approach is implemented, the types of information that can be generated using the system, approximate times to solutions, and the way in which the strategic model can be used to control the spatial model. In particular, the case studies will illustrate the flexibility of the approach and its ability to address spatial planning problems at multiple scales. In all examples, Woodstock generated optimal harvest schedules, and Stanley produced spatially feasible harvest block patterns. Solutions were generated on a Dell Dimension XPS Pro 180n personal computer (180 MHz Pentium Pro) with 64 Mbytes of memory, running Windows NT. It is worth noting that all of the examples required no more that 16 Mbytes to solve.

Case One

This example illustrates the effect of varying spatial regulations on final blocked solutions. The case study is drawn from a moderate-sized pine forest located in the Southern United States. The tract covers approximately 212,000 acres and is comprised of 31,917 polygons for an average of about 6.6 acres per polygon. The forest is a complex mosaic of large pine plantations, cypress ponds, and natural pine. Many of the older plantations exceeded 1,000 acres, well beyond the 120-acre opening size limit, and the geographic data set had been preprocessed to subdivide the large polygons into several smaller pieces. Figure 1 illustrates a small section of this forest.

In this case, the strategic objective was to maximize present net value subject to even-flow harvest and ending inventory constraints over a 40-year planning horizon. Stands were eligible for thinning and clearcut logging, as well as preharvest cultural treatments such as herbicide application. The LP matrix generated by Woodstock was 3,300 rows by 34,000 columns and 136,000 non zero elements. Woodstock produced the matrix in about 3 minutes and CWHIZ (Ketron 1992) found an optimal solution in about 2 minutes.

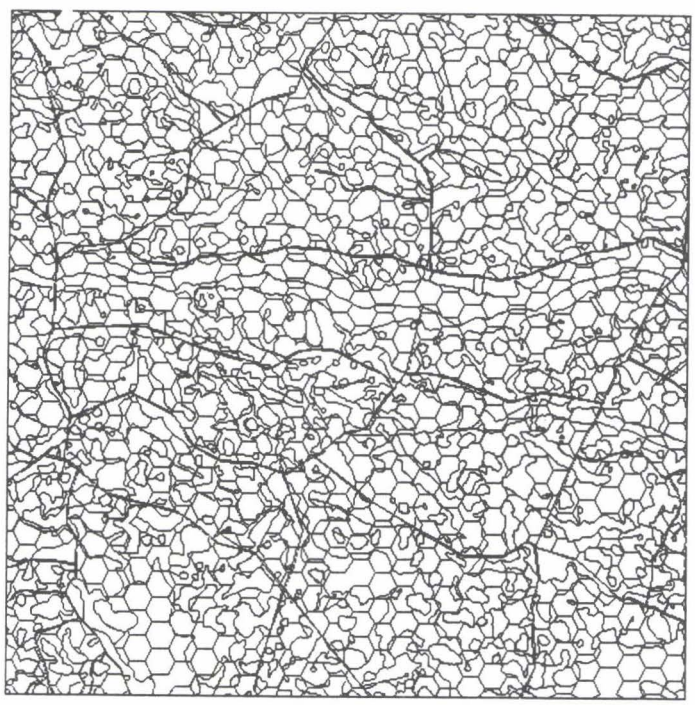

Figure 1.—*Forest used in case one. Note the hexagon grid used to divide stands.*

Table 1.—*Results of 11 Stanley runs using different minimum and maximum block sizes and adjacency delays*

Run	1	2	3	4	5	6	7	8	9	10	11
Min. block (acres)	0	5	10	20	10	10	10	10	10	10	10
Max. block (acres)	-	-	-	-	120	120	120	120	120	500	-
Adjacency delay (years)	0	0	0	0	1	2	3	4	5	5	5
Impossible area (percent)	0.0	0.9	2.2	5.1	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Max. block (acres)	1093	1270	867	753	120	120	120	120	120	499	890
Avg. block acres)	60	78	92	115	53	39	44	52	52	75	90
Score (percent)	99.1	98.2	96.6	94.4	95.3	94.5	92.7	89.3	81.3	89.3	89.9

While a significant portion of the present net value was generated from commercial thinning, Stanley scheduled only clearcuts. When commercial thins were included in the Stanley runs, loss due to blocking was reduced by almost half (e.g., run 9 scores were increased to almost 91 percent of optimal). However, commercial thins had much less restrictive spatial constraints than clearcuts and were intentionally omitted so as to extend the effects being demonstrated. Values for each of the runs in table 1 were generated by running Stanley for approximately 5 minutes; within that time Stanley generated approximately 500-600 different layouts, each time retaining the layout that yielded the highest score.

Since most of the harvest scheduling problems have already been solved in the strategic phase, Stanley requires very few input parameters. Those that seem to have the greatest effect on solutions are adjacency delays and the minimum and maximum acceptable opening size (Jamnick and Walters 1991). In this forest, harvest blocks were considered adjacent if they were within 300 feet of one another. The blocks were subject to a 5-year green-up delay, a maximum opening size of 120 acres, and a minimum acceptable block size of 10 acres (table 1, run 9).

In addition to statistics such as minimum, maximum, and average block size, Stanley calculates a score signifying how close it was able to come to the strategic optimal solution. It was expected that Stanley could not exactly match optimal solutions since Woodstock did not consider stand-level spatial constraints. When spatial constraints were imposed and tightened, we expected the scores from Stanley to decrease accordingly. When constraints were light, Stanley generated solutions that were very close to the strategic optimal. For example, in run 6, Stanley blocked 94.5 percent of the optimal even though 2.2 percent of the area was impossible to block. In other words, Stanley was able to block 94.5 percent of the strategic optimal solution using only 97.8 percent of the eligible forest. As constraints became more limiting, scores were reduced (table 1).

The results of the Stanley runs show two key effects on the final blocked solutions. First, as the minimum acceptable block size increased, so did the area impossible to block (Table 1, runs 1-4). This effect was attributed to the structure of the forest and not the approach and/or algorithms. The impossible area represents stands or collections of stands that cannot be blocked because of their location in the forest. Often these stands are isolated from others by features such as buffers, rivers, or lakes. When Stanley attempts to create harvest blocks, no configuration exists that will allow these stands to be included.

Second, as the maximum opening size decreased and the adjacency delays increased, scores were reduced. To a large extent, the reduction is a function of the forest (age classes and homogeneity of stand types within the forest, for example). However, as the adjacency delay increased relative to stand rotations, the magnitude of the reductions increased. In this forest, a 5-year adjacency delay was approximately one-quarter of the average plantation rotation, the cost of which was much higher than in a forest with longer rotations. Relaxing the maximum opening size limit resulted in higher scores when the adjacency delay was long (table 1, run 9 vs. run 10). In this situation, Stanley alleviated adjacency conflicts by aggregating conflicting harvest units to form larger blocks with a single timing choice.

Figure 2.—*Forest used in example two. Stands in the north zone are shown in light grey and stands in the south zone are shown in dark grey. Buffers and other excluded areas are shaded black.*

Case Two

Case two illustrates how changing the nonspatial model can affect the resulting block layouts. This forest in Western Canada is 3,191 hectares (ha) in size and contains 3,034 individual polygons. It is dominated by large tracts of even-aged lodgepole pine intersected by many trails, roads, and seismic lines (fig. 2). For analysis, the forest was classified into a northern zone and southern zone. Regulations dictated that cut blocks not exceed 100 ha and that there be a 20-year green-up delay. The minimal acceptable harvest block size was specified as 10 ha.

The strategic objective was to maximize the first-period coniferous volume subject to an even-flow harvest over a 200-year planning horizon, while maintaining at least 600 ha of mature coniferous forest in every period. Stands were eligible for clear-cut harvesting, after which they could either be naturally regenerated or site-prepared and planted. Two models were generated by Woodstock; harvesting was unrestricted in the first, while in the second, the north zone was inaccessible for the first seven decades. The matrix generated for the unrestricted model contained 2,400 rows by 9,900 columns and 48,000 nonzeros, and the restricted model had 2,200 rows by 8,200 columns and 39,000 non-zeros. Both were generated and solved in under 1 minute. As expected, the restricted model's optimal solution was lower than the first (around 10 percent less).

Both strategic solutions were run through Stanley for 100 years into the future. The only difference between the two runs was the strategic harvest schedule used by Stanley—the spatial constraints were identical in both cases. In the first case, Stanley blocked 95.6 percent of the strategic optimal solution after 5 minutes (over 4,600 alternative layouts evaluated), and blocks were distributed throughout the entire forest (both management zones) in all periods. In the second case, 96.1 percent was blocked after 5 minutes, and no harvest blocks were located in the north zone prior to period seven. It is worth noting here the way that the results were produced. Using the hierarchical approach, we were able to control the general location of blocks by changing the strategic model, which is a relatively simple process, and not the spatial model, which would be a much more complex operation.

Case Three

The final example represents a large operational scale problem representative of the type of problem faced by forest planners today. Case three comes from a large tract of land in Eastern Canada. The forest covers approximately 176,884 ha and is comprised of 88,843 polygons, averaging about 2 ha per polygon. The forest is being intensively managed for softwood pulp and logs. Stands were eligible for several pre-harvest treatments including planting, spacing, and thinning; harvest treatments included clear-cut and two-pass logging. The forest is highly fragmented, containing numerous riparian buffers, habitat exclusion zones, and roads. Figure 3 depicts a small section of the forest.

The strategic objective was to maximize spruce-fir harvest volume subject to even-flow harvest and ending inventory constraints over an 80-year planning horizon. Additional constraints limited the production of hardwood volume and the amount of planting and spacing within each planning period. The periodic change in the area within broad forest cover types was also limited to maintain biodiversity levels over the long term. The LP matrix generated by Woodstock was fairly large, approximately 9,800 rows by 71,000 columns and 922,000 nonzeros. Woodstock produced the matrix in about 15 minutes and CWHIZ found an optimal solution after about 35 minutes.

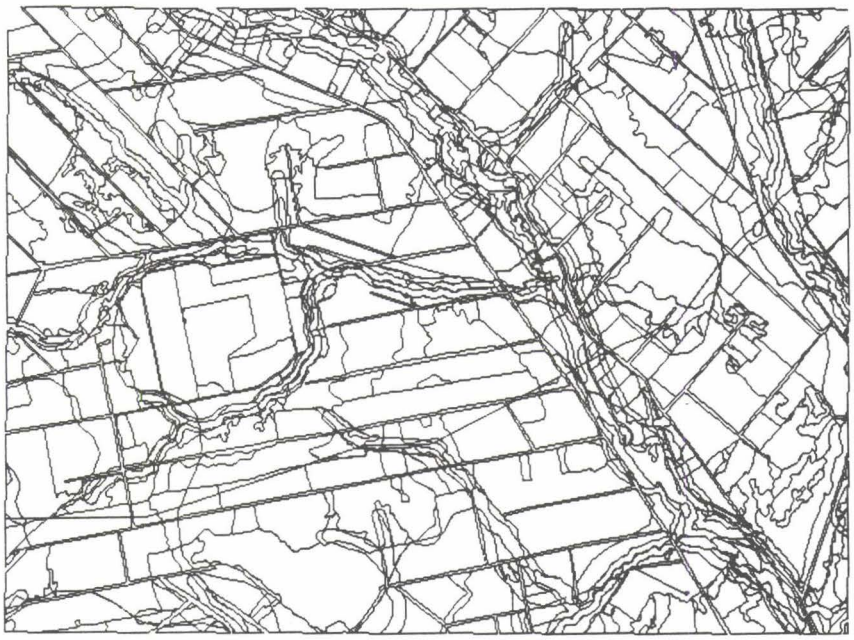

Figure 3.—*Forest used in example three. Area shown represents 1 of the 76 map sheets in the entire forest.*

Spatially feasible harvest blocks were created for 25 years into the future, subject to a maximum opening size on clearcuts of 100 ha, a minimum acceptable block size of 5 ha, a 10-year adjacency delay, and maximum harvest flow fluctuation of 10 percent. Two Stanley runs were required to allocate all of the harvest activities to blocks because the spatial restrictions for partial harvest activities were different than those for clearcut harvesting. The first Stanley run (clearcuts) evaluated about 1,000 different block layouts in around 30 minutes while the second run (partial harvest) required about 35 minutes. In both cases, the layout that provided the highest score (nearest to optimal) was kept. When the results from the two runs were combined, Stanley was able to allocate 89.8 percent of the strategic optimal. The final block layout contained 4,000 harvest blocks ranging in size from 5 to 100 ha with an average of 45 ha.

The ability of the approach to deal with problems of this size is well illustrated in this case. To carry out a similar analysis using the more traditional approaches, including manual blocking, would take something in the order of weeks, if not months, to produce a single block layout, rather than the thousands produced in a matter of hours using this approach.

SUMMARY AND CONCLUSIONS

In summary, the system is based on a hierarchical approach introduced by Jamnick and Walters that greatly simplifies the solution of the overall problem. It demonstrates that the spatial complexity of the problem can be increased and solved without increasing the complexity of the spatial algorithm. In effect, the two phases worked together to solve a more complicated problem.

The three case studies presented show that the approach works at various spatial scales on realistic-sized problems and considers long-term trade-offs. Pseudospatial resolution, in which subforest areas are recognized, can easily be accommodated in this planning phase, allowing for the distinction of features such as watersheds, management units, forest districts, etc. An essential factor is that long-term trade-offs and constraints are handled in the strategic phase, and that the software required to allocate stands to specific periods (spatial phase) can therefore be much simpler. Also, since the long- and short-term phases are so closely linked, any changes to the strategic model are directly communicated to the spatial stage.

Work is ongoing to refine the system.

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LINEAR APPROACHES TO SPATIAL OPTIMIZATION

John Hof and Michael Bevers[1]

ABSTRACT.—This paper documents formulations for four different spatial optimization problems that use linear (continuous-variable) programming. For more discussion on these problems, the models, and case study results, the reader is referred to our forthcoming papers: Bevers *et al.* (1997), Hof *et al.* (in preparation), Hof (in review), and Hof and Raphael (in press).

THE BLACK-FOOTED FERRET

Early in 1987 the black-footed ferret (*Mustela nigripes*) became one of the world's most endangered mammals when the last known free-ranging member of the species was taken into captivity. The Wyoming Game and Fish Department was successful in breeding six of the surviving ferrets, setting the stage for a national recovery program of releasing captive-bred ferrets back into the wild. The first release of captive-bred black-footed ferrets occurred in 1991 in Shirley Basin, Wyoming. Two additional reintroduction areas were added in 1994, including the site of our study, the federally managed lands of the Buffalo Gap National Grassland adjacent to the Badlands National Park.

Available evidence strongly supports the conclusion that black-footed ferrets have narrow habitat requirements, living principally in prairie dog burrows and depending primarily on prairie dogs for prey (Linder *et al.* 1972). The spatial arrangement of prairie dog colonies in a colony complex has important effects on the number of black-footed ferrets that can be supported (Minta and Clark 1989). As prairie dog colonies become smaller or more widely separated, successful ferret dispersal between colonies is less likely and the total population that can be supported is reduced.

Within the reintroduction area, black-footed ferret habitat comprises a complex of active and potential prairie dog colonies (patches) forming distinct habitat "islands" on the landscape. The approach described here is related to earlier biodiffusion models (Skellam 1951, Kierstead and Slobodkin 1953, Okubo 1980), and island biogeography models (Allen 1987). Our spatial optimization model uses discrete time periods and approximates habitat patch configurations with a grid of cells on the landscape. We then incorporate cellular habitat management decision variables so that all potential spatial configurations can be considered (within the resolution of our grid). Ferret population growth and dispersal between cells from year to year is modeled here with an exponential population growth potential and a random dispersal pattern that relates probability of dispersal to distance. With discrete spatial cells and time periods, this reaction-diffusion process can be captured with linear constraints, as described below.

Particular ferret habitat layouts are achieved over time by the prairie dog populations that result from rodenticide treatment-nontreatment schedules applied to each cell across the landscape, on the premise that prairie dog populations will recover rapidly in areas left untreated. Decision variables (X_{ihk}) are defined for each possible schedule (indexed by k) of annual rodenticide treatment or nontreatment in each habitat condition class (indexed by h) for each cell (indexed by i). For example, one schedule could call for rodenticide treatments in the first year and every fourth year thereafter, while another schedule might call for treatments to begin in the second year instead. Adult black-footed ferret populations expected in each cell in any year are limited by either the carrying capacity of that cell, or by the ability of ferrets from nearby cells to successfully reproduce and disperse there, or both. Additional decision variables (R_{it}) are used to determine the timing (year t) and location (cell i) for captive-bred ferret releases into the area. Our spatial optimization model is:

(1) Maximize: $\sum_t F_t$ (1)

(2) subject to: $F_t = \sum_i S_{it}$; $t = 1,...,T$

(3) $S_{i0} = N_i \ \forall i$

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(4) $S_{it} \leq R_{it} + \sum_j g_{ji}(1 + r_j)S_{jt-1)} \quad \forall i \; ; \; t = 1,...,T$

$; \sum_i g_{ji} \leq 1 \quad \forall j$

(5) $\sum_i R_{it} \leq b_t \quad ; \; t = 1,...,T$

(6) $S_{it} \leq \sum_{h=1}^{m_i} \sum_{k=1}^{n_{ih}} c_{ihkt} X_{ihk} \quad \forall i \; ; \; t = 1,...,T$

(7) $\sum_{k=1}^{n_{ih}} X_{ihk} = A_{ih} \quad \forall i,h$

(8) $\sum_i \sum_{h=1}^{m_i} \sum_{k=1}^{n_{ih}} c_{ihktp} X_{ihk} \leq C_{pt} \quad \forall p \; ; \; t = 1,...,T$

$X_{ihk}, \; S_{it}, \; R_{it} \geq 0 \quad \forall \; i, h, k, t$

Where:

t indexes annual time periods (0,...,T) that begin in late spring when the young emerge from the den

i,j index habitat management cells in the study area

h indexes initial habitat condition classes in each cell

k indexes rodenticide treatment schedules

p indexes policy constraints (if any) on selection of habitat management variables

X_{ihk} = amount of area (in hectares) in cell i and initial habitat condition class h allocated to the k^{th} multi-year habitat management schedule

R_{it} = number of captive-bred ferrets released in cell i during year t that are expected to survive adaptation to life in the wild

S_{it} = expected adult ferret population (including yearlings) in cell i at the beginning of year t, plus R_{it}

F_t = expected adult ferret population for the entire complex in year t

N_i = actual or estimated initial number of adult ferrets in cell I

g_{ji} = proportion of surviving adult and juvenile ferrets from den areas in cell j in year t-1 expected to disperse and become adult ferrets in cell i at the beginning of year t

r_j = an "r-value" for ferrets in cell j reflecting the maximum expected annual net population growth rate (i.e., when habitat is not a limiting factor)

b_t = an upper bound on the total number of captive-bred ferrets released during year t expected to survive adaptation to life in the wild

c_{ihkt} = expected adult black-footed ferret carrying capacity for cell i and condition class h in year t per hectare allocated to X_{ihk}

m_i = number of initial habitat condition classes in cell I

n_{ih} = number of habitat management schedules being considered for initial habitat condition class h in cell I

A_{ih} = total prairie dog colony area (in hectares) of initial habitat condition class h in cell I

c_{ihktp} = c_{ihkt} if X_{ihk} contributes to policy constraint p in time period t, and zero otherwise

C_{pt} = amount of total expected black-footed ferret carrying capacity allowed in time period t under policy p from the relevant subset of X_{ihk} habitat management variables.

Equations (1) - (5) define a discrete-time reaction-diffusion system (in this case, population growth and dispersal) for evaluating population persistence within a habitat complex. Equation (1) maximizes total expected adult black-footed ferret population for all time periods, each summed by equation (2). Equation (3) sets initial population conditions. Equation (4) limits the expected adult ferret population in any cell for any year to (at most) the number of captive-bred ferrets released into the cell plus the number of ferrets expected to disperse into the cell from all cells in the complex (including the same cell), after accounting for net reproduction during the previous year. Equation (5) limits the number of ferrets that can be released during any given year.

Our model assumes that organisms relocating into unsuitable regions will perish. This mechanism provides a probabilistic basis for the expectation that, after accounting for births and deaths due to all causes in an abundant habitat setting through the r-value (net annual population growth rate r_j), additional mortality will occur in proportion to the usage of inhospitable surroundings. Equations (6) and (7) account for these habitat dynamics by imposing black-footed ferret carrying capacity constraints in each cell as a function of the selected habitat management (rodenticide treatment) schedules. The expected ferret population in any cell in a given year (S_{it}) is determined by either equation (4) or (6), whichever is limiting. We employed equation (8) to limit the total amount of ferret habitat in the National Grassland in order to examine spatially and temporally efficient tradeoffs between expected adult ferret populations and levels of prairie dog population control. The linear dispersal model (equation 4) is based upon an assumption of purely random diffusion, which is a first-level approximation for highly developed species like the black-footed ferret. In general, biased diffusion enhances the persistence of populations (Allen 1983). Thus, our model provides an estimated lower bound on the size of the expected population. Note that we have identified the r_j growth rates by cell. In some cases, expected net reproduction may be different from one cell to another even with abundant habitat. For example, one cell may lie closer to terrain frequented by predators than another cell.

BLACK-TAILED PRAIRIE DOGS

Once regarded as nothing but pests, the ecological importance of the prairie dog (*Cynomys* sp.) is now more completely understood (Hoogland 1995, Cincotta *et al.* 1988). To allow for analysis of black-tailed prairie dog (*C. ludovicianus*) recovery strategies, we are working with the Nebraska National Forest to build a model for the Conata Basin Area of South Dakota. The formulations presented here reflect our current thinking and will be tested further in this case study. We will identify patches of potential black-tailed prairie dog (simply "prairie dog" hereafter) habitat, based on historic maps of prairie dog presence during a time of high populations. These irregular patches are contrasted with the cellular grid utilized in the previous section. Those patches will be assumed to be the only part of the landscape that can support prairie dog populations, and thus they will limit our choice variables. The choice variables will determine the area within each patch of potential habitat that is zoned for prairie dog habitat. It is assumed that grazing regimes will be applied in the areas zoned for habitat that are conducive to prairie dog presence, and poisoning will be eliminated. Areas in the patches of potential habitat that are not zoned for prairie dogs will be assumed to be subject to poisoning and other management actions that make them unsuitable for prairie dog occupation.

In order to model the prairie dog, we must make some specific assumptions about its population dynamics. First, we assume that at any point in time, prairie dog populations in any colony are determined by whichever is limiting: population growth and dispersal processes or the habitat carrying capacity determined by our choice variables. Second, we will assume that, if unconstrained by habitat, prairie dog populations grow exponentially with an "r-value" that indicates a growth rate net of natality and mortality.

Third, the only prairie dog movements that we will model are those that result in net dispersal between habitat patches. This means that intra-patch movements and animal "exchanges" between patches for breeding purposes (which roughly balance out) will be ignored. Hoogland (1995, p. 87-88) states "Emigration to, and colonization of, new colony sites probably is expensive and dangerous for prairie dogs...However, expansion of already existing colonies should be easier and safer." Also, Cincotta *et al.* (1988, p. 31) state that "Results indicated that prairie directly adjacent to the study colony was likely to be colonized if it was near a dense population of prairie dogs...High population densities may force prairie dogs to expand into new territory." Prairie dogs probably begin to disperse to other areas before their colonies become completely saturated, but as a conservative modeling approach, we will assume that no dispersal emigration occurs until habitat areas are at carrying capacity, determined with a fixed parameter (per unit of habitat).

Fourth, we will assume that once dispersal occurs, it is random. Thus, we will identify a probability for each pair of patches that a dispersing prairie dog from the first patch will successfully disperse to the other patch. This probability can reflect barriers to dispersal (and other landscape features), but will primarily be a function of the distance between the two patches (Garrett and Franklin 1981). Our model will be structured so that dispersal between all patches of potential habitat will be determined simultaneously. Implicit in this simultaneous solution will be a feature that if prairie dogs attempt to enter a habitat area that is already full, those animals will then return to the pool of dispersers and will again be subjected to the probabilities of successful dispersal to the other patches.

Fifth, we will assume that dispersing prairie dogs will not reproduce during their first year in the new colony. As Cincotta *et al.* (1987, p. 341) states: "There was no observed reproductive success during either 1982 or 1983 among the newly established populations of prairie dogs on the treated site. This suggests that female black-tailed prairie dogs disperse after the mating season and do not bear young during their first year in a newly established territory."

The combination of highly population-dependent random dispersal and zero reproduction during the first year in a new territory, creates a model of spatial prairie dog recovery that can be contrasted with the population dynamics assumed for the black-footed ferret in the first section.

Our model is formulated as follows:

(9) Maximize: $\sum_{t=1}^{T} \sum_{i=1}^{M} S_{it}$

(10) Subject to: $X_i \leq A_i \quad \forall\ i$

(11) $S_{i1} \leq N_i \quad \forall\ i$

(12) $Q_{i1} = O \quad \forall\ i$

(13) $S_{it} + Q_{it} \leq (1+r)S_{i(t-1)} - \sum_{j \neq i} rg_{ij}\ Q_{j(t-1)} + \sum_{j \neq i} g_{ij}\ Q_{jt}$
$\forall\ i,\ t=2,\ldots,T$

(14) $S_{it} \leq C_{it}X_i \quad \forall\ i \forall\ t$

(15) $\sum_{i=1}^{M} X_i \leq B$

Where:

i = indexes patches, as does j
M = the number of patches
t = indexes time periods
T = the number of time periods.
S_{it} = the prairie dog population in patch i, time period t
X_i = the number of acres in patch i zoned as prairie dog habitat
Q_{it} = a variable used to account for the prairie dogs that leave patch i in time period t to disperse to other patches.
A_i = the number of acres in patch i. Patches are defined as areas of potential prairie dog habitat.
N_i = the initial population of prairie dogs in patch i.
r = the "r-value" for resident prairie dogs.
g_{ij} = the probability of a dispersing prairie dog successfully leaving patch j and inhabiting patch i.
C_{it} = the density, or carrying capacity, of prairie dogs, per acre of habitat.
B = a limit on the total amount of area zoned for prairie dog habitat (policy parameter).

Equation (9) is the objective function, and maximizes the total prairie dog population over all patches and time periods. Equation (10) limits the zoned habitat to the potential habitat in each patch. Equation (11) limits the population in the first time period to the initial population. Equation (12) initializes the number of dispersing prairie dogs to zero. The population in each patch and time period, S_{it}, is determined by whichever of constraints (13) or (14) (or (11) for the first time period) is binding. Equation (14) simply limits the prairie dog population to the habitat carrying capacity determined by the solution values for X_i. Equation set (13) determines the population of each patch i in time period t, if it is binding, as follows: The population from the previous time period for patch i, $S_{i(t-1)}$ is expanded by a factor of (1+r). In order to account for the dispersing prairie dogs not reproducing during their first year in a new colony,

$$\sum_{j \neq i} r g_{ij} \; Q_{j(t-1)}$$

is deducted from $(1+r)S_{i(t-1)}$.

Then, the prairie dogs successfully immigrating from other patches ($j \neq i$),

$$\sum_{j \neq i} g_{ij} \; Q_{jt}$$

are added. If, for a given i, Equation (14) is binding, then the excess population in (13) is accounted for in the Q_i variable, which simultaneously enters into the other equations in (13) as dispersing prairie dogs. The model solution will always set $Q_{it} = 0$ until Equation (14) is binding because the sum of the S_{it} is being maximized and $\sum_{j \neq i} g_{ij}$ is always less than one. Thus, no dispersal occurs until allocated habitat (X_i) is full, as desired. Equation set (13) is a simultaneous system of equations which will solve for all Q_{it} and Q_{jt}—simultaneously accounting for all dispersal between all patches in the given time period. Equation (15) limits the total of the X_i across all patches, as a policy constraint.

EXOTIC PEST CONTROL

Recent literature documents the important and expanding problem of exotic pests invading forest ecosystems. As Haack and Byler (1993) summarize, "most native insects and pathogens reach a dynamic state of equilibrium with their hosts and natural enemies. However, this situation may not be true for ... newly introduced exotic insects and pathogens." These authors also state "Exotic insects and pathogens have dramatically altered forest ecosystem diversity, function, and productivity. More than 20 exotic fungal pathogens and 360 exotic insects now attack woody trees and shrubs in North America ..." This section will investigate the possibility of using optimization methods to assist in developing a spatial management strategy for an invading pest once it has arrived and has at least minimally established itself.

In order to construct a solvable optimization formulation, we use discrete time periods and discrete units of space as in the ferret model—square cells located in a north-south coordinate system. Liebhold *et al.* (1995) (originally Skellam 1951) suggest "Fick's law of diffusion" to model the dispersal of an invading organism. An exponential population growth model is then combined with Fick's model in Liebhold *et al.* In order to apply this approach with discrete time periods and cells, we treated each time period as a "time of release" and each cell as a "point of release." Any diffusion model (such as Fick's) can then be used to predict the dispersal into other cells during the length of one time period. We can thus calculate a matrix of coefficients, g_{nh} that indicate the proportion of population that disperses from each cell, indexed with n, to each other cell, indexed with h, during one time period (and using cell centroids to calculate distances). The diagonal of this coefficient matrix, where n = h, indicates the proportion of the population that remains in each cell during each time period. With those coefficients calculated, we can then model the population in each cell h in each time period as:

$$(16) \quad S_{ht} = \sum_{n} g_{nh} \left[(1+r_n) \; S_{n(t-1)}\right] \qquad t = 1,\ldots,T \;\; \forall \; h$$

$$S_{no} = N_n \qquad \forall n$$

Where:

h and n both index cells

t indexes time periods (t=0 for initial conditions)

r_n = the r-value for cell n

S_{ht} = the pest population in cell h in time period t

$S_{n(t-1)}$ = the pest population in cell n in time period t-1

N_n = the initial pest population in cell n

This combines an exponential growth function with the diffusion coefficients for discrete time periods and discrete space units (cells) in a linear, convex formulation. The g_{nh} coefficients in (16) can be varied to reflect spatial variation across the landscape but must be assumed constant over time (more precisely, across all time periods). This means that no limits to host capacity are included in (16); just as they are not included in Liebhold *et al.* 1995. If it is possible to reduce pest population through spatially-specific management actions, then (16) could be augmented as:

$$(17)\quad S_{ht} + \alpha_h\ y_{ht} = \sum_n g_{nh}\ [(1+r_n)\ S_{n(t-1)}] \qquad t = 1,...,T \quad \forall\ h$$

$$S_{no} = N_n \qquad \forall\ n$$

where:

Y_{ht} = the amount of management effort in cell h and time period t

a_h = the pest population exterminated per unit of Y_{ht} in cell h

Any number of economic or biological objective functions could be utilized, but for simplicity let us assume that we wish to minimize the total exotic pest population over T time periods. Let us also assume that our management resource limitation can be captured by a simple constraint that specifies that we are only able to apply K_t units of management in each time period t. The problem, then, is to optimally locate the management-induced pest mortality over time, given the initial pest infestation location and subsequent growth and dispersal (as it is affected by the management actions).

The basic optimization model is then:

Minimize:

$$(18)\quad \sum_{t=1}^{T} \sum_n S_{ht}$$

Subject to:

$$(19)\quad S_{no} = N_n \qquad \forall\ h$$

$$(20)\quad S_{ht} + \alpha_h\ Y_{ht} \geq \sum_n g_{nh}\ [(1+r_n)\ S_{n(t-1)}] \qquad t = 1,....,T \quad \forall\ h$$

$$(21)\quad \sum_h Y_{ht} \leq K_t \qquad t = 1,...,T$$

Equation (20) is written as an inequality in the model, because that aided in avoiding numerical problems in model solution.

This model assumes that management (Y_{ht}) can be meaningfully related to the exterminated pest population. In situations where management options must be related to host elimination (e.g., sanitation cutting of a host tree species), the reader is referred to the approaches in Hof *et al.* (1997). The host-based problem appears to require integer programming approaches, which severely limits model size and therefore spatial resolution. If management effort can be directly related to pest mortality, but with diminishing returns, this can be included in the optimization model above through piece-wise approximation.

THE NORTHERN SPOTTED OWL

For more than a decade, conservation of the northern spotted owl (*Strix occidentalis caurina*), hereafter referred to simply as "the owl," has been a central issue in management of forests in the Pacific Northwest. We used a simulation model to construct an optimization model with a simplified formulation of the spatial biological processes and relationships that allows linear optimization. We then used the simulation model to "check" the conclusions drawn from optimization—thus recapturing the biological detail and reliability that might be compromised in the simplified optimization formulation. Following Holthausen *et al.* (1995), we divided the Olympic Peninsula into hexagonal 1,500-ha cells, the size of which represents a core area or territory for an owl pair. This yielded a model with 1,681 cells (41 x 41), with the carrying capacity set at zero for any cell that does not currently contain any habitat. To simulate the spotted owl population, we used OWL (version 2.01, described by McKelvey *et al.* 1992).

The basic variables in this problem are the amount of habitat in each cell that is retained (or protected). Because habitat for the northern spotted owl is low-elevation late-successional and old-growth forest, which take hundreds of years to develop, the decision to retain habitat in any cell or not is semi-permanent. Thus, we used a static optimization model to try to take advantage of this simplifying characteristic. This implies that the dynamic processes of birth, dispersal, and death modeled in the simulation model had to be captured in an equilibrium sense with static relationships in the optimization model.

The dynamics of owl population growth and dispersal captured in the simulation model are complex, but we assume that at any point in time, the population in any cell is limited by either the amount of habitat, the connectivity to other cells' owl populations, or both. A simple characterization of connectivity would be that

each cell's population is potentially limited by the population in the cells immediately surrounding it. For each cell i, we will then define the set of immediately-surrounding cells as set Ω_i. This simple relationship is analogous to a first-order spatial autocorrelation; and, because each cell in each Ω_i is affected by its surrounding cells, this relationship implies a cascading effect beyond the Ω_i set for each cell i. The combination of potentially limiting factors could then be formulated as:

$$(22) \quad p_i \leq f\left(\sum_{k \varepsilon \Omega_i} p_k\right) \quad \forall\, i$$

$$(23) \quad p_i \leq g\left(C_i\right) \quad \forall\, i$$

Where:

i indexes the cells.

p_i = the population in the i^{th} cell.

Ω_i = the set of cell indexes that surround cell i.

C_i = the proportion of cell i that is retained as habitat.

$\sum_{k \varepsilon \Omega_i} p_k$ = the total population in all of the cells in set Ω_i

f and g = empirical functions

The f and g functions do not describe dynamic processes, but are, instead, static, deterministic relationships estimated from empirical or simulated observations. The f and g functions would, in general, be nonlinear, but can be approximated in a linear optimization model, so long as they exhibit diminishing returns. We thus formulate a model to maximize owl population as:

$$(24) \quad \text{Maximize:} \quad \sum_{i=1}^{I} p_i$$

Subject to:

$$(25) \quad p_i \leq \sum_{j=1}^{J} a_j X_{ij} \quad \forall\, i$$

$$(26) \quad X_{ij} \leq S_j \quad \forall i \forall j$$

$$(27) \quad \sum_{j=1}^{J} X_{ij} = \sum_{k \varepsilon \Omega_i} p_k \quad \forall\, i$$

$$(28) \quad p_i \leq \sum_{h=1}^{H} b_h Y_{ih} \quad \forall\, i$$

$$(29) \quad Y_{ih} \leq Q_h \quad \forall\, i \forall\, h$$

$$(30) \quad \sum_{h=1}^{H} Y_{ih} = C_i \quad \forall\, i$$

$$(31) \quad O \leq C_i \leq B_i \quad \forall\, i$$

Where:

j indexes the J segments that approximate f

h indexes the H segments that approximate g

a_j = a coefficient that approximates the f function for the j^{th} segment of $\sum_{k \varepsilon \Omega_i} p_k$

b_h = a coefficient that approximates the g function for the h^{th} segment of C_i.

X_{ij} = the j^{th} segment of $\sum_{k \varepsilon \Omega_i} p_k$

Y_{ih} = the h^{th} segment of C_i

S_j = the segment size limit of X_{ij}

Q_h = the segment size limit of Y_{ih}

B_i = the fixed proportion of habitat currently existing in cell i, and thus available for retention

Equation (24) is simply an owl population-maximizing objective function. Equation (25) approximates the (f) connectivity functions with the X_{ij} segments, defined in Equations (26) and (27). Equation (28) approximates the carrying capacity functions (g) with the Y_{ih} segments, defined in Equations (29) and (30). Equation (31) limits the habitat retention variables, C_i, to be less than or equal to the amount of habitat in each cell that is available for retention (B_i). The expected population in each cell (p_i) is determined by whichever (or both) of Equations (25) and (28) are limiting.

To estimate the connectivity (f) function, we began by selecting cells from the study area where spotted owls were least likely to be habitat-limited. Available evidence suggests that owl survival (and hence, likelihood of occupancy of a cell) does not increase when habitat exceeds 60 percent of a cell (Bart 1995). There were 100 cells that had > 60 percent habitat, which we included for the function estimation. Given that these 100 cells are not habitat-limited, we assume that the populations observed in the simulation runs are determined by the presence of population in surrounding cells. Next, we ran 50 replications of 100-year simulations. We estimated "population" of each cell as mean occupancy, the number of years the cell was occupied by a pair of owls divided by the total years in the simulation (100). Using average simulated population numbers across all replications for each of the 100 selected cells, we then regressed each cell's mean

population against the total mean population of the six cells surrounding it. We tried several functional forms, but settled on a log-log transformation that yielded an exponential function. The statistical confidence in these equations was quite good with R^2 values of ~0.9. We also inspected plots to assure that the functions were reasonable relative to the plotted data. These functions were then approximated in Equations (25) - (27).

As with the connectivity (f) functions, we used simulation model results to estimate the carrying capacity (g) functions to be as consistent as possible with the assumptions that were used in the simulation model. We plotted mean owl occupancy per cell against percent habitat in each cell from simulation replications based on retention of all current habitat, thus maximizing connectivity within the limits of the study area. We approximated this relationship with three segments that have diminishing slopes (in Equations (28) - (30)). We did not statistically regress these relationships because of the logical requirements that the intercept term had to be non-negative, and the function had to be "convex" (exhibiting diminishing returns). Based on visual examination of the plots, the functions assumed are good approximations, but it is possible that the carrying capacity (g) functions are somewhat sigmoidal (e.g., logistic). Unfortunately, this functional form would create a nonconvex program in the optimization model, and the approximation of the carrying capacity function would require integer methods (mixed integer programming or separable programming). This nonconvex model would not be solvable with nonheuristic methods that ensure optimality at the scale of our case study. This is a good example of the simplifications necessary to make the optimization model solvable, even given the basic simplicity of the formulation in the first place.

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ECOSYSTEM MODELING USING SPECTRUM AND RELMDSS: ANALYZING VEGETATIVE SUCCESSION FOR FOREST PLAN REVISIONS

James Merzenich and Miles Hemstrom[1]

ABSTRACT.—This paper explains methods for scheduling management treatments using vegetative succession class acreage goals and the stratification of environmental variables as the guiding principles. The SPECTRUM linear programming model schedules treatments to meet vegetative goals while considering the risk of catastrophic loss due to fire and other causes. The RELMdss model allocates the SPECTRUM solution to subdrainage, where tradeoffs associated with meeting standards and guidelines or working within work force and budgetary limitations can be evaluated. This hierarchical planning approach is essential to ensure that goals are realistic and that the treatment levels called for can be achieved.

INTRODUCTION

Much of the forested area of the interior Columbia River Basin was historically dominated by open stands of ponderosa pine maintained by frequent ground fires. Many stands in these areas are now overstocked with grand fir, Douglas-fir, and small ponderosa pine. The composition of the remaining forested land has been substantially altered largely as a result of active fire suppression and timber harvests (Campbell and Leigel 1996). Recent drought and insect epidemics have caused substantial tree and stand mortality in many areas. Grassland and shrub habitat has also been significantly impacted by factors such as livestock grazing, juniper encroachment due to fire suppression, and the invasion of nonnative grasses and weeds (Keane *et al.* 1996). This results in vegetative conditions and hazards that are now well outside natural bounds.

One proposed goal of ecosystem management is to restore vegetative conditions to a more natural state. To accomplish this goal, it is often useful to compare existing vegetation or management alternatives to a historical range of variability (HRV) (Caraher *et al.* 1992). For each vegetative type, or succession class, HRV is defined as the minimum and maximum acreage that should be maintained within each class through time. In theory, if vegetation is maintained within these historic bounds, the species and communities that evolved within them can persist. HRV depends on disturbance regimes, such as natural fire and insect outbreaks, which vary according to the environment. This conceptual framework is the basis of the Interior Columbia Basin Ecosystem Management Project (ICBEMP) effort.

This paper describes a methodology for modeling vegetative succession, using HRV and the stratification of environmental variables as the guiding principles. The SPECTRUM linear programming model linked with a RELMdss disaggregation model can be a useful tool for this analysis. The SPECTRUM model schedules treatments to meet HRV goals while considering the risk of catastrophic loss due to fire or other causes and maintaining essential habitat for all species. The RELMdss model allocates the SPECTRUM solution to subdrainages or other divisions of the forest where the trade offs associated with meeting standards and guidelines or working within work force and budgetary limitations can be evaluated (Church *et al.* 1995). This hierarchical planning approach is essential to ensure that the goals of the forest plan are realistic and that the treatment levels called for in the plan can be achieved.

A primary objective of plan revisions is to determine the level of treatments necessary to move the existing vegetation towards a desired state in the coming decade. Treatments include prescribed and natural fire and commercial and noncommercial harvest activities. Long-range multidecade analysis is needed to ensure that improvements in ecosystem health are sustainable and that conflicts related to ecosystem management are resolved. The following sections discuss the basic information needed to support this modeling effort.

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A Classification of the Vegetation Based on Existing and Potential Conditions

The existing vegetation should be classified on the basis of cover type and structural stage using succession classes developed by the ICBEMP. Cover type is determined by the dominant species for range and forest types. Dominant species are calculated by canopy coverage for range types and by basal area for forest types (Keane *et al.* 1996). Structural stages define the physical condition of a stand at different states of development (Oliver and Larson 1990).

The potential vegetation type (PVT) is determined and mapped from biophysical characteristics of the site. PVT or environment maps are most useful at plant association group resolution. The classification of the potential and existing vegetation must be consistent across national forests to ensure that data can be aggregated to support provincial and regional analysis.

Desired Future Conditions or Goals for the Vegetation

The acreage that should be in each succession class through time must be estimated. Acreage goals may be based on the HRV and other factors. HRV should be described by plant association group.

Management Prescriptions Designed to Manipulate Vegetation or to Manage Risk Due to Wildfire or Other Causes

Through partial cutting and other treatments one can shorten or prolong the time a given stand stays in one succession class. A stand may be driven towards an earlier or later class by removing selected species. Prescribed burning and other fuel management prescriptions may lessen the probability of a catastrophic wildfire. Economically efficient design of these prescriptions is essential to develop an overall strategy that can be implemented within budgetary constraints.

Successional Pathways Must be Described for Each PVT

These pathways are a temporal map of the succession classes contained in each PVT and include the probable effect of fire and other disturbances. The management of risk due to wildfire, insects and disease, and other factors must be an integral part of any model used to determine treatment needs. Pathways should be described between succession classes (cover type and structural stage) by plant association group.

The Vegetation Dynamics Development Tool (VDDT), developed for the ICBEMP effort, stochastically projects changes in vegetative composition over time as affected by natural and human-caused disturbances (Beukema and Kurz 1995). This tool is useful for building successional pathway diagrams and understanding the relationship between environmental variables. The sensitivity of the system to changes in alternative assumptions are also easily evaluated with VDDT. VDDT will be used in forest plan revisions to test assumptions prior to inclusion in other models. VDDT may also be used iteratively with SPECTRUM to evaluate the possible consequence of a large-scale stochastic disturbance on the selected treatment schedule.

A Methodology for Predicting Disturbance Rates at the Stand and Landscape Level

Disturbance probabilities and changes in succession that follow a disturbance have been estimated by the ICBEMP team for wildfire, insects and disease, and many other factors. These disturbance data are also loaded into VDDT models. One initial task is summary and aggregation of these data into a form useful for plan revisions.

The probability that a vegetative stand will burn (or be affected by any disturbance event) is a function of both the stand condition itself plus the condition of adjoining stands from which a fire may spread. In general, a stand's condition affects the probability of a fire start. The spatial configuration of stands and their associated fuels influence the expected size and intensity of a wildfire. A methodology is needed to make initial estimates of fire probabilities and to adjust these probabilities with time as landscape conditions change. Disturbance models should be stratified by succession class and plant association group.

MODELING TOOLS

The general purpose of vegetative modeling for plan revisions is to determine if and when ecosystem goals are attainable, and to develop reasonable treatment schedules to meet those goals. These models are *strategic* in scope and are not intended to identify actual stands where treatments will occur.

No single analytical model can develop a forest-wide management strategy that can be implemented on the ground. A hierarchical modeling approach, where each successive model provides input to the next model, is needed to achieve this task. The following sections describe the individual models.

VDDT

VDDT will be used to define successional pathways and examine the potential effects of disturbance agents on the

vegetation. This model enables one to quickly analyze the sensitivity of the system to changes in disturbance assumptions, prior to running SPECTRUM.

SYSDYN

SYSDYN is a dynamic simulation model that has been developed for the Blue Mountains. It estimates the annual burned acres based on random fire events under variable weather conditions (Wiitala *et al.* 1994). The level of fuel treatments, such as prescribed burning, can be introduced into this model to estimate burned acres per decade. This or a similar model will be used to help generate expected burn probabilities for the SPECTRUM model.

SPECTRUM

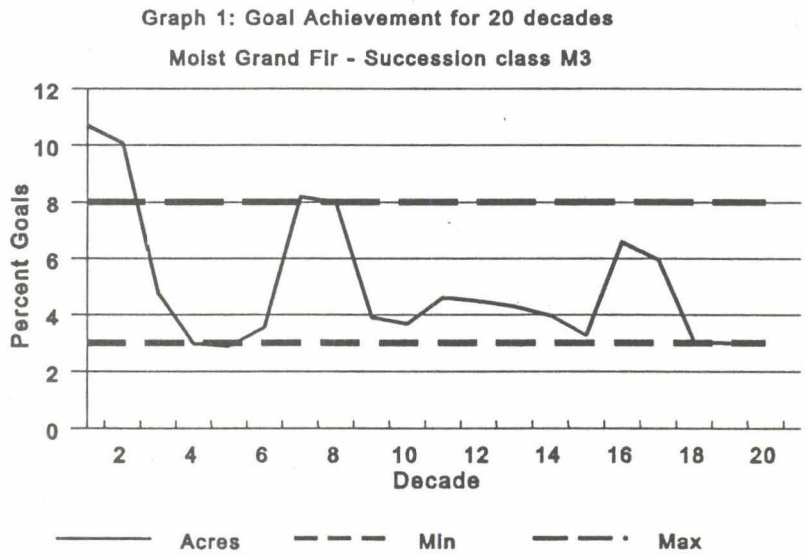
The SPECTRUM model schedules the treatments necessary to achieve vegetative acreage goals, while considering the role of stochastic disturbance agents described in the VDDT and SYSDYN models. Two features of the SPECTRUM linear programming model enable this analysis: (1) a GOAL option allows one to easily set a target range for each succession class acreage objective; and (2) Model 2 capabilities allow direct modeling of fire mortality and other disturbance factors.

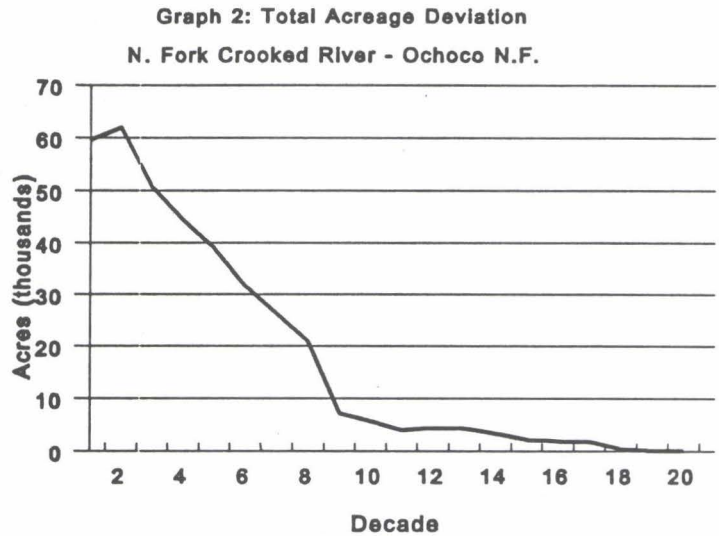
A prototype SPECTRUM model has been developed for the Ochoco National Forest to assess their viable ecosystem approach to management (Ochoco National Forest 1994). This model schedules treatments to meet vegetative (HRV) goals while considering the risk of catastrophic loss due to fire or other causes. The model objective is to minimize the number of acres outside the historic range of variability. Weights are placed on goals for each plant association group and succession class based on relative importance. The effect of the nondeclining timber flow requirement and other legal requirements are also evaluated. Economic or treatment acreage limits are included to insure a realistic solution that can be implemented within budgetary and work force limits.

Two sample graphs, derived from a completed goal programming run for the North Fork Crooked river drainage of the Ochoco Forest, are shown here. The goal achievement for one succession class is displayed as figure 1. The min and max lines on this graph represent the historic range of variability or goal for this class. The acres line represents the linear program solution for 20 periods. Note that the acreage within stage M3 initially exceeds the desired range. From the 3rd to 20th decade, the acreage fluctuates widely but stays within the desired range of 3 to 8 percent.

Figure 2 shows the acreage deviation for the entire drainage for 20 decades. This deviation is the sum of 45 separate goals applied to each combination of a plant association group and succession class. Initially 60,000 acres are outside the desired range. The deviations sharply decline in the succeeding decades as the model treats acres to meet the vegetative goals.

Automated procedures have been developed to build SPECTRUM models and interpret solutions. To build models, data are imported from GIS and other sources into relational data bases and are then automatically converted into the SPECTRUM format. The results of model runs are exported to data bases and spreadsheets where they can be viewed, summarized, and graphed.





SPECTRUM model results are nonspatial. Other tools are needed to estimate the location of proposed treatments. Linear programming models are also deterministic by design. That is, for each set of assumptions there is only one optimal solution. By making multiple runs with varying assumptions, the sensitivity of the solution to data changes can be evaluated.

RELMdss

The RELMdss model is a goal-based, visually interactive LP model. In this hierarchical approach, the RELMdss model is used to display the SPECTRUM solution and then redistribute the solution to meet standards and guidelines that apply to geographic subunits of the forest. For example, elk thermal cover requirements could be evaluated for winter ranges while equivalent clearcut limits are applied to watersheds. The main purpose of RELMdss is to fit the SPECTRUM solution to the scale at which each standard and guideline applies. This may result in a decline of treatment opportunities as compared to the SPECTRUM solution. The RELMdss model calculates and displays treatment opportunities for up to six decades.

The RELMdss model operates in real time and visually displays the results of each run on a computer screen map. In this way users can immediately identify the standard, guideline, or physical constraint that is most limiting in any area. With RELMdss users can also quickly enable or disable standards and guidelines. This allows quick sensitivity analysis of the factors that affect the available treatment acreage.

SUMMARY

No single analytical tool is capable of developing a treatment schedule for a National Forest that can be implemented on the ground. The authors propose a hierarchical approach that uses VDDT and other tools to assess the role of natural and human-caused disturbance agents; uses SPECTRUM to select treatments on the basis of meeting vegetative goals; and uses RELMdss to distribute these treatments to subdrainages while complying with area-specific standards and guidelines

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LANDSCAPE ANALYSIS OF STRUCTURE, PATTERN, AND FIRE EFFECTS IN THE SIERRAN MIXED CONIFER FOREST

K.M. Menning[1]

ABSTRACT.—A century or more of fire suppression has altered forest structure and pattern in the American West and in many places around the world. These changes in the return interval, extent, and intensity of fire have resulted in increases in forest density, fuel loads, and fire risk. These latter changes have effects on wildlife habitat and understory biodiversity; forest structure, composition, and regeneration; ecosystem functioning; fire behavior, including susceptibility to catastrophic fire; and risk of epidemic loss to insects and disease due to a more homogeneous forest structure. To restore pre-settlement forest structure and pattern and reduce fire risk a number of scientists recommend restoration of the forests.

Analysts advocating restoration of forests to recover to historic conditions while minimizing risks have advocated two general approaches. *Structural restorationists* would alter forest structure to historic conditions by silvicultural (mechanical) treatment such as thinning followed by the reintroduction of fire. They argue first, that prescribed fire in unthinned stands could result in stand-replacing fires and second, that historic forest conditions could not be achieved since forests become more homogeneous during the period of suppression. *Process restorationists* would restore native processes—fire—directly, without first modifying fuel loads, with the goal of recreating historic forest structures. Process restorationists maintain that one or two sequential prescribed fires, carefully planned and managed, would begin to re-establish forest condition with little risk of catastrophic loss to fire. They argue that reintroducing fire directly is more cost effective and avoids undesirable ecological side effects introduced by structural restoration. The implications of this debate have profound significance to managers wishing to restore forest conditions and ecologists wishing to understand fire ecology, disturbance regimes, and multiple pathways of succession.

Little information exists to address this debate, however, particularly from the process-restoration point of view. In order to support restoration and fire implementation decisions we need to have better information on both the current and post-fire conditions of forests. The research described in this prospectus involves collecting data on landscape forest structure and pattern in the Mineral King watershed of Sequoia National Park, California. A team of managers and scientists from the National Park Service, U.S. Geological Survey, and National Interagency Fire Center have chosen this watershed to test the practicality of reintroducing prescribed fire at a large scale. High resolution, multispectral remote imagery is available for the entire watershed from prior to the onset of prescribed burning and similar data will be collected after the burns occur. Additionally, data are collected in the field to ground-truth the remote imagery and provide ecological information on in-stand forest conditions not available from above.

This research is divided into several questions. First, what is the range of historic structure and pattern of the mixed conifer forest in this area? Second, how does prescribed fire alter structural, compositional, and spatial diversity and complexity in the forest? Third, using the answer to question two, can prescribed fire be used to restore forest condition to the state or range of variability described in the answer to the first question, i.e., "does process restoration work?"

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In order to address these questions we are collecting data from three time periods—historic, current, and post-fire—and at two spatial scales—in-stand and between-stand. By examining the condition of the forest in each of these six time-space categories and measuring the change between them we should have a better sense of how the absence of prescribed fire and its reintroduction affect this important forest type in the Sierra Nevada and what the implications may be for restoration efforts. In a decision support capacity, this ecological information will feed back into planning to achieve ecological goals and, indirectly, into event management of individual fires for safety, fuels management, and strategy.

RESOLUTION OF SMALL-GROUP SELECTION IN FOREST PLANNING MODELS

T.M. Barrett, R.C. Heald, and F.G. Schurr[1]

ABSTRACT.—Forest planners must make tradeoffs between size and complexity of planning models and the accuracy of predictions. Modeling small-group selection poses particular difficulties because of inherently high spatial resolution and probably high temporal resolution. In addition, small-group selection is likely to be a recently adopted technique imposed on an already heterogeneous landscape; long complex conversion periods are required before regulation. This paper discusses some of the techniques that can be used to incorporate small-group selection into forest planning models in the context of tradeoffs between accuracy and simplicity. Possible modifications from even-age planning techniques that may be needed include: (1) approaches to inventory, (2) projections of growth and yield, (3) tracking of individual units through space and time, and (4) classification of forest structure. Current knowledge limitations on how small-group selection affects wildlife, aesthetics, and growth may temper the need for complex modeling approaches.

INTRODUCTION

Early in this century, Carl Schenck described small-group selection as cuts, from 0.4 to 1.2 ha in size, that could be "roundish, oval, square, etc. as the case may be, usually coinciding with a geological feature" (Schenck 1905). He noted disadvantages to the group selection method such as scattered operations and the need for an intricate system of permanent roads. For these and other reasons, small-group selection has never been used extensively in the United States. However, in recent years, there has been increasing interest in the method. The small openings of group selection are similar to small-scale disturbance by wind, insects, or root disease (Tappeiner *et al.* 1997), leading some people to view small-group selection as a silvicultural system well suited to ecosystem management. In 1992, a strategy that would have greatly increased the use of small-group selection was considered for National Forests in the Sierra Nevada region (Fiske *et al.* 1992). If small-group selection becomes more prevalent, planners will need to anticipate issues involved in modifying forest planning models to incorporate this system.

Forest planning models are used to develop information about the consequences of different alternatives for forest management. Incorporating small-group selection into forest planning models poses some problems. First, less information is available on biological, ecological, and economic effects of small-group selection than is available for methods such as clearcutting. Second, small-group selection has an inherently high degree of spatial and temporal resolution, leading to potentially greater complexity in planning models. In this paper, we discuss the respective merits of different approaches to planning for small-group selection, and use some 20 years of group selection at Blodgett Forest Research Station (University of California - Berkeley) to illustrate the potential problems and opportunities.

CHOICES FOR MODEL RESOLUTION

Daniel *et al.* (1979) defines a stand as a "reasonably homogenous unit that can be clearly differentiated from surrounding stands by its age, composition, structure, site quality, or geography". However, by convention, the term *stand* is applied to an area of group selection, rather than to the individual groups. Smith (1986) suggests that this convention arose before the advent of air photos, when mapping stands on the ground made it too time consuming to delineate very small areas.

In what Smith refers to as *balanced* uneven-age management, an equal proportion of a stand's area is in each age class; in his discussion of uneven-age management, the

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distinguishing characteristic between single-tree selection and small-group selection is that the area of an individual patch of same-age trees is larger under small-group selection (Smith 1986). With balanced uneven-age management, there is a continuum of management from single tree selection to even-age management that differs by the size of individual openings in the canopy cover. The boundaries defining group selection might be placed at opening sizes from 0.10 to 1.00 ha, with single tree selection being anything smaller and even-age management being anything larger.

If an uneven-age stand is balanced, then it can also be perceived as a small version of a regulated forest under even-age management. In this case equal productive areas are occupied by each age/size class ranging from 0 through R, where R is the rotation age or largest tree size class. As the site quality of a stand managed under small-group selection is presumed homogenous, harvest volumes in a regulated state would be the same under either volume control or area control. As with area regulation for even-age management, the percent of area harvested at each entry is equal to the rotation age divided by the time interval between entries. For example, using an 80 year rotation with a 10-year entry interval, an eighth of the stand's area would be put into small group cuts at each entry; for a 100 ha stand with a desired group size of 0.5 ha, 25 individual group cuts would be placed at each entry.

Hann and Bare (1979) recognized that linear programming (LP) models could model either even-age systems, uneven-age systems, or a mixture of systems with equal facility. Yet there can be some differences in the size of the model created. As an example, consider converting a homogenous forest area to either (1) single tree selection or (2) an even-age silvicultural system, where planning periods are 10 years and after regulation both systems have the oldest trees in an 80-year age class. Modeling the even-age system would require eight decision variables to represent each initial entry. With a 10 year cutting cycle, the single tree selection system would be represented with a single decision variable. In the representation of the even-age system, groups of trees of the same age are treated as individual variables, and in the representation of the uneven-age system, groups of trees of different ages are treated as individual variables. Modeling for uneven-age management can create significantly smaller LP models.

Modeling for small-group selection could conceivably use either approach. In typical planning models, modelers decide whether to work with individual stands or with stand-types. In planning for small-group selection, they must choose between four options for what is to be the highest level of spatial resolution:

1. groups,
2. stands,
3. group-types, or
4. stand-types.

Higher resolution will lead to larger planning models, so that the most compact model will be produced by using stand-types as the basic land unit. However, the level of resolution can affect accuracy of predictions. For a planning model used to predict economic outputs, timber volumes, and changes in vegetation structure, the predictions are dependent on inventory, initial land classification, projection of growth and yield, acres harvested by entry, assumed economic coefficients, and method of structure classification. To discuss each of these points, we use as an example 20 years of small-group selection at Blodgett Forest Research Station, located in the mixed conifer region of the Sierra Nevada.

UNCERTAINTY OF PREDICTIONS

Inventory

As small-group selection has not been widely used, it is likely to be imposed upon stands that have had a different past management regime. If no groups of different ages currently exist, it would take at least one rotation to convert the stand to a balanced state. In order to maintain the same level of accuracy, sampling intensity for forest inventory has to increase with increasing variation of the stand. Thus, a sampling design suitable for the stand at the start of the conversion period may not be suitable for the same stand at the end of the conversion period.

The 1,200 ha Blodgett Forest has a permanent inventory system with 0.04 ha plots located at 120 m intervals throughout the forest. Less than 162 ha are currently managed with group selection. The permanent regularly spaced inventory system works well for the areas of the forest managed with single tree selection and even-age management, but is less suitable for small-group selection management, due to its gradual conversion to high spatial variability. Systematic sampling methods can be biased when applied to populations with periodic variation. Small-group selection is particularly prone to bias because of uniformity of size and spacing of the group cuts. Blodgett's permanent regularly spaced sampling system estimates inventory for the residual stand well, but may not capture changes from group cuts (fig. 1). In this case, the sampling system is most suitable for low resolution modeling with stand-types, and least suitable for high resolution modeling which would be better served with stratified sampling.

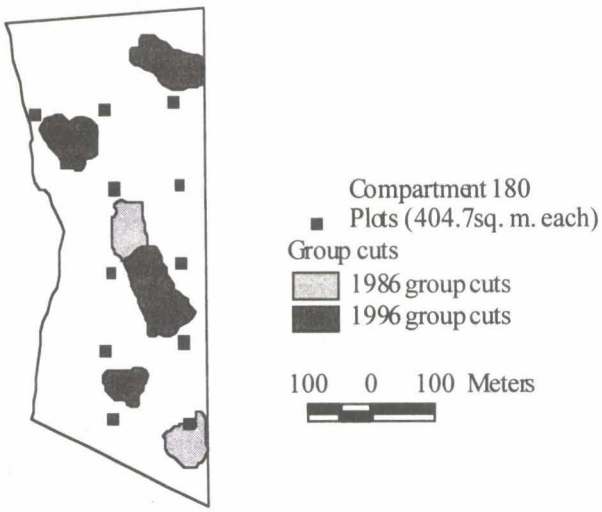

Figure 1.—*Inventory plots and two sets of group cuts for compartment 180 at Blodgett Forest Research Station.*

Initial Classification

Typical methods of stand delineation (air photo interpretation or remote sensing with digital image classification) will often distinguish individual groups. When individual groups are distinguished, sophisticated programming could be needed to get a classification method to recognize a pattern of group cuts as a unique stand. Because a small-group selection stand consists of patches of differently sized trees, even classification by ground mapping or air photo interpretation will not be able to distinguish all edges.

Classification methods can cause problems if the groups are very small or variable in size. Depending on the shape of the group, classification of thirty meter resolution remote sensing imagery might consistently identify groups of 0.50 ha or more, but miss groups of 0.10 ha. Classification of remote sensing imagery may not differentiate between recent clearcuts and recent group cuts without using the size of the cut as an attribute for classification. As growth of regeneration is somewhat affected by the size of openings, the ability to differentiate land in clearcuts from land in group cuts can be important.

The classification problems are most likely to occur when managers have not kept track of past harvesting and have outdated inventory information. Because of the problem of edge delineation, and the inexact typing that can occur with vegetation classification, it would probably not be efficient to keep track of groups and group-selection stands with periodic vegetation classifications. Instead, for management efficiency, it would be desirable to spatially delineate groups soon after they are first harvested, using either a global positioning system (GPS), ground mapping, or air photo interpretation, and keep that information in a geographic information system (GIS) along with the date of harvest and a record of any treatments.

Growth and Yield Projections

Growth and yield models used to project inventory and harvest volumes typically are either whole stand models or spatially independent single tree growth and yield simulators. Either type of projection assumes spatial homogeneity for the modeled stand. Growth and yield models are not designed to model the types of patchy stands produced with small-group selection. Using the permanent plot inventory system at Blodgett with an individual tree growth and yield simulator, growth projection could take any one of three approaches:

1. To simulate the growth of individual plots in the stand (or stand-type), and then average the results.

2. To average the plots in the stand (or stand-type) to create a "representative" plot, and then simulate its growth.

3. To stratify plots by the age of groups they represent, average the plots within each age class, and simulate the growth of the averaged plots.

4. To stratify small plots within groups by distance to edge, simulate growth of individual plots, average results by strata, and weight by the proportion of area within zone of edge distance.

None of these choices is very satisfactory. For any of these approaches, the growth and yield simulator would not correctly account for competitive interactions along the edge of group cuts. Of course, using individual tree growth and yield models to simulate the growth of stands (or stand-types) always ignores effects of edge. But the problem is compounded in modeling growth of trees in a group selection system, because of the high percentage of area within the zone of edge influence.

The size of group openings affects both species composition and growth rates of regeneration (Dale *et al.* 1995, McDonald and Abbott 1994). A study of 8- to 12-year-old regeneration in group cuts at Blodgett Forest found the highest number of seedlings (< 1 m tall) to be located within 5 to 10 m from the edge, perhaps because of favorable microclimate and increased seedfall (Olson and Helms 1996). However, sufficient taller trees at all distances from edge occurred to make this effect unimportant. Compared to even-age plantations, regeneration in the group cuts at Blodgett includes a higher proportion of shade tolerant Douglas-fir and White fir, and a smaller

proportion of shade intolerant Ponderosa pine. However, sufficient regeneration of each of the six major species allows pre-commercial thinning to achieve any desired species mix.

In the group cuts at Blodgett, planted 2-year-old seedlings are used to accelerate regeneration growth, although natural regeneration would be sufficient to produce full stocking. Average height growth of regeneration in group cuts is less than in even-age plantations, with the greatest effects occurring within 1/3 of overstory tree height from the edge. However, at 15 years of age, the growth of the best 200 trees per acre in the group cuts exceeds the projections of Oliver and Powers (1978) for pine plantations (table 1). Thus from a modeling point of view, early pre-commercial thinning allows one to greatly reduce problems caused by using even-age growth estimates for young regeneration in group cuts

Although not measured at Blodgett, the edge trees in the residual stand that surround a group cut are likely to benefit from the increased growing space. McDonald *et al.* (1996) found that Ponderosa pine, Sugar pine, Douglas-fir, Incense-cedar, and White fir surrounding 18 and 27 m diameter group cuts all experienced significantly increased basal area growth. It was concluded that individual growth of trees adjacent to openings was influenced by tree size, distance from opening, and position of other trees (McDonald *et al.* 1996).

The problem of adjusting growth projections for edge influence is compounded by changes in the nature of the edge over time. The first group cuts at Blodgett were surrounded by 60- to 80-year-old forest. Group cuts that will take place near the end of the conversion period could have edges bordering either groups of 15 year old saplings or groups of 160 year old trees. The dynamic nature of edge interactions poses significant complexity if it is necessary to project growth of group selection stands with a very high degree of accuracy.

When there are no edge interactions, we have found that growth and yield simulators can be surprisingly accurate in projecting short term growth of managed 60- to 90-year-old forest. Using the CACTOS individual tree growth and yield model (Wensel *et al.* 1986), a paired T-test of 79 remeasured tenth acre plots found that the projected annual volume growth was within 1.5 percent of measured growth (no significant difference at a = 0.05). However, the CACTOS model is not designed for projecting stands beyond this age. Projection of small-group selection is complicated by the long conversion period needed to get to a regulated system. If the stand is already mature when group selection is first implemented, the last groups of trees to be harvested will be outside of the range that we can accurately estimate with current knowledge. A mitigating factor to this problem is that progressively less area will be occupied by such "beyond model data range" trees.

Economics and Management

Harvesting costs are likely to be higher with small-group selection than with clearcutting (Schaffer *et al.* 1993, Kellogg *et al.* 1996). However, on tractor ground, increased logging costs with small-group selection may be minor compared to effects of stumpage price changes (Keegan *et al.* 1995). All of Blodgett Forest is suitable for tractor ground; harvesting costs for small-group selection are typically more than harvesting costs for clearcuts ($70/Mbdft) and less than harvesting costs for individual tree selection ($85/Mbdft) or commercial thinning. Harvesting costs per unit volume, and damage to the residual stand, decrease when the diameter of the group opening is more than 1 overstory tree height. To minimize damage to the residual stand, a group diameter of at least 2 tree heights is preferred.

Other costs for managing small-group selection may also be higher than corresponding costs for even-age management. In some cases, road system costs may be higher. At Blodgett, road costs are unrelated to silvicultural method, as the forest is covered by a permanent and well-maintained road system. Costs of planting, brush treatment, and pre-commercial thinning in group cuts at Blodgett are slightly higher than in clearcuts due to longer travel times, with travel cost increasing with crew size. In the past, a simple sketch of group location on

Table 1.—*Height in meters of ponderosa pine regeneration in groups, yield tables, and plantations*

Source of growth estimate	Height at 10 years	Height at 15 years
Groups[a]	4.1	5.9[c]
Groups[1] - best 494 trees per ha	6.6	8.2[c]
Oliver and Powell (1978) - 6 ft spacing	3.4	6.4
Oliver and Powell (1978) - 12 ft spacing	4.0	7.0
Plantation[b]	6.2	11.9

[a] Each value averaged from 6 groups, 10-year and 15-year measurements from different stands
[b] 10-year and 15-year measurements from different stands
[c] Differed from 10-year groups by not having pre-commercial thin at 6 years

stand maps has sufficed to prevent individual groups from becoming "lost". Periodic air photos also help ensure that all groups are accounted for and receive planned intermediate treatments. GPS units are currently being used to map group boundaries, with the resulting information becoming part of the forest's GIS database. Increased administration cost for tracking treatment of group cuts is minor. Within the past decade, average net revenue for logs delivered to the mill has more than doubled. Although there is uncertainty about the estimates of harvesting, treatment, and management costs for small-group selection, it is overwhelmed by the volatility of timber prices.

Inaccurate estimates of the size of group cuts may be a source of error in prediction of costs and revenues. The inability to estimate area harvested does not, intuitively, make a great deal of sense. A manager should be able to harvest exactly the proportion of the stand that is planned for harvest. Yet going back to Schenk's (1905) definition of group selection, it is apparent that part of the original appeal of group selection was the ability to place individual groups in particular locations. These locations may be chosen to reduce a less desired species, to remove a center of high mortality, to replace slower growing individuals, or to harvest small groups of trees with a higher economic value than the surrounding stand. If one of the desirable aspects of group-selection is the discretion given to the forester, than group cuts will vary in size, shape, and location regardless of a modeling system that treats the problem as a standard conversion to a miniature regulated forest. Although the general intention at Blodgett is to use the equivalent of a 100 year rotation, past entries exemplify the variability that can occur (table 2).

Part of the variability shown in table 2 was deliberately chosen to compensate for patches of advanced regeneration that existed before the first set of group cuts. If a stand is already "patchy" before implementation of the group system, managers can either account for this when they plan the location and size of group units (for example, see Heald and Haight 1979) or keep to an area-regulation approach by harvesting equal areas at each entry. The manager may also wish to deviate from an area-regulated group system if working with a mixed-species type. At Blodgett, only Ponderosa pine and Sugar pine need openings at the sizes of small-group selection in order to successfully regenerate and grow. Other species (Douglas-fir, White fir, and Incense-cedar) regenerate successfully with single tree selection. Thus a manager might want to manage a stand with a mixture of larger openings (small group selection) for patches dominated by pines, and smaller openings (single tree selection) to regenerate shade tolerant species. With this mixed silviculture approach, planners can still choose to model either by groups or by stands, but will need to think through the problems of estimating growth and future forest structure.

Classification of Forest Structure

As with initial land classification, inventory systems, and projection of growth and yield, the projection of future forest structure can be set at either the resolution of individual groups or at the resolution of group-selection stands. California forest practice rules currently recommend the use of the California Wildlife Habitat Relationships (CWHR) system (Airola 1988) to help assess impacts of forest management on wildlife habitat. Unfortunately the classification system does not currently make a distinction between a multi-canopied stand that is spatially homogenous, and the spatially heterogeneous multi-canopied stand produced by small-group selection. Thus by this system, small-group selection stands would be classified as the same type as an equivalent single tree selection system.

One could consider a group selection stand to consist of an assemblage of habitat types corresponding to even-age management: i.e., set resolution of forest structure at individual groups. If the composition of future forest structure is evaluated within the linear programming model through the use of tracking rows, the model will not be able to distinguish between even-age management and small-group selection. As the size and pattern of forest harvest units can have important ecological consequences (Franklin and Forman 1987), this treatment will also be unsatisfactory.

Table 2.—*Percent of compartment area harvested by entry*

Comp.	Entry A		Entry B		Average over two entries
	Date	% of area	Date	% of area	% of area
50	1985	7.4	1996	11.9	9.7
180	1986	3.7	1996	10.6	7.2
270	1985	6.3	1995	7.5	6.9
380	1985	14.8	1995	5.0	9.9

One possible approach would appear to be to create a new set of classes of forest structure to account for the types produced by small-group selection. Yet although one of the benefits of group selection may be that it mimics fine scale natural disturbances (Tappeiner *et al.* 1997), there has been little research to assess the impacts of small-group selection on wildlife habitat or ecological processes. The problem of what level of resolution to use for classification of the forest structure produced by small-group selection is tempered by an inability to predict how the forest structure can be related to either wildlife populations or other ecological effects.

CONCLUSION

The ideal resolution for small-group selection in a linear programming-based forest planning model will depend on the types of consequences that must be predicted, the degree of accuracy desired for those predictions, the inventory information available, the available methods for projection of growth and yield, and the time and personnel available for modeling. In general, setting model resolution at the level of individual groups will not be practicable given the increase of model size and the prohibitive cost of collecting information at this scale.

Growth and yield modeling will probably require modeling by individual group type, given the lack of spatially dependent models that could correctly account for edge effects. Some calibration or adjustment of outputs may be advisable, to decrease predicted growth of regeneration and increase predicted growth of older groups. If group types need to be modeled individually by growth and yield models, outputs for group types would need to be combined if the linear programming model resolution was to be set at the level of stands or stand-types. Given the extra expense of this processing, it may be preferable to simply set LP model resolution at group types.

We believe that one of the desirable characteristics of the small-group selection system is the latitude practitioners of silviculture have to make fine-scale decisions about the placement and size of harvest units. Thus, for small ownerships, there is some conflict between the need to allow for flexibility and the need to predict accurately. Uncertainty is undesirable for planning, but the flexibility that generates uncertainty is a desirable trait of the small-group selection silvicultural system. Viewing the conversion of forest to a small-group selection system as conversion to a "balanced" stand is conceptually useful, but likely to be inaccurate for small areas.

We have included the small-group selection units into Blodgett's planning model, using group-types as the basis for growth and yield modeling, and stands as the resolution in the LP model. Modeling small-group selection was more time consuming and more difficult than modeling the other silvicultural systems. It was also less accurate in prediction of growth, harvest, and future forest structure type. Yet the difficulty of planning and administration for small-group selection is a minor consideration compared to other factors that influence the selection of the appropriate silvicultural system.

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THE PIPELINE PROBLEM: A TACTICAL LEVEL APPROACH LINKING FOREST LEVEL PLANNING TO PROJECT PLANNING

Joseph P. Roise and Lawrence Hayden[1]

ABSTRACT.—A case study of the problem of developing a schedule to plan projects is presented along with the integer goal programming formulation used to link strategic forest plans with operational project plans. The difficulty of coordinating project plans using the old compartment-based order-of-entry system with the new forest plan management area designation is discussed. The solution required the creation of larger land groups for project planning and the coordination of human resources between districts.

INTRODUCTION

The purpose of this paper is to recount a specific instance of forest plan implementation and report on an approach for linking outputs established by a strategic plan to the planning and implementation of individual projects. Optimal solutions had the role of providing a logical starting position in the planning process.

The National Forest System in the United States uses two levels of planning: strategic forest planning and project planning. Strategic planning is the process for establishing management directions, focusing on issues of public concern, explaining how management will affect key sites, producing important outputs, and protecting vital resources and ecosystems (U.S. Congress 1992). Strategic forest plans are made for an entire national forest using a longtime horizon. Project planning is a process for achieving the conditions and outputs established in the strategic plan. A project plan is made for an area that is usually smaller than the whole forest (for example, a watershed, compartment, or management area) for a time period limited to completion of the project (usually only a few years). A project plan is at the operational level of the hierarchical planning classifications system: strategic, tactical, and operational (Gunn 1991). In the Southern Region, a compartment order-of-entry system achieved one phase of tactical level of planning.

The Southern Region of the National Forest System has been managing project planning (ultimately timber resources) using a systematic order of entry by compartment for about 30 years. The order-of-entry system began in the 1960's. The land was stratified by "compartments," which averaged about 1,000 acres each. The centerpiece of compartment planning was the compartment prescription, prepared by silviculturists, which assigned treatments in every compartment at least once in 10 years. During any year, compartments planned for treatments were widely distributed across the district to assure a diverse age class mix. This disbursal entry scheme has influenced the timber resources available today. In the mid-1980's, the entry sequence became disrupted by land allocations made in forest plans. Management areas in the forest plan did not coincide with compartment boundaries and lands "not suitable for timber production" now average about one-third of each compartment. These major disruptive factors resulted in difficulty in achieving an even flow and orderly sequence of timber management activities. Therefore, adjustments to the compartment entry sequence were needed to account for the new forest plan decisions.

The compartment order-of-entry sequence provided a tactical link between forest strategic goals and projects. Staff officers commonly use the term "pipeline" to summarize the project-planning work sequence. Many activities and goals must be coordinated within each project-planning undertaking. Many projects must be in various stages of completion at all times in order to keep the "pipeline" flowing (fig. 1). The term also conveys the time delay for a project plan to move from start to completion. At a base level, a forest has an allowable sales quantity (ASQ) which it desires to meet on a yearly basis. To achieve the ASQ, a sufficient number of project plans must be completed each year. Up to a year earlier (even longer in some areas), project planning must have been started in several areas in order to meet current ASQ.

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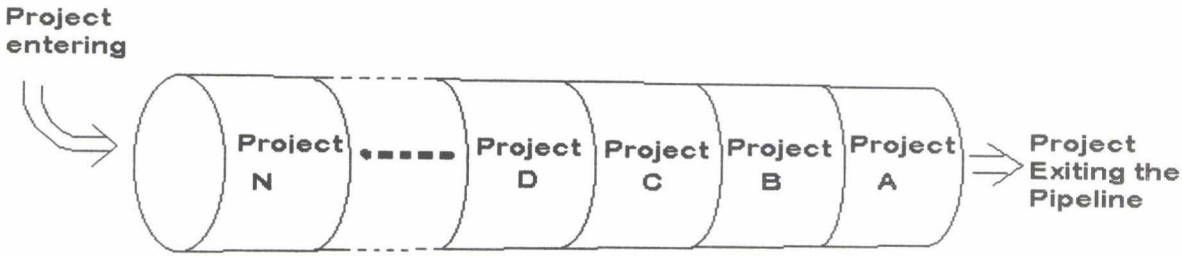

Figure 1.—*The pipeline contains a series of project plans in different states of completion from start to finish. If there is an interruption of projects entering the pipeline, or if there is a bottleneck in the pipeline, the amount of projects exiting may not satisfy forest goals.*

The development of each harvest project on a national forest takes so long because of the number of resources which must be analyzed, the amount of detail in which they must be analyzed, and the legal requirements which must be met. When developing a strategic forest plan, the information available and required is extensive, and the detail required for a project plan is usually not available. The information needs for a project plan are much more detailed and site specific than required for a forest plan, but before these can be collected, a decision must be made on which area of land to survey and analyze. The survey is labor intensive, requiring several types of specialists (table 1). The decision on where to plan is a tactical management problem of how to best link strategic to operational levels. A decision to analyze an area must be made before analysis can begin.

Table 1.—*Some of the surveys and specialists required by law in the development of a harvesting project*

Survey objective	Specialist
Archeology	Archeologist
Threatened and endangered species	Biologist
Roads and access	Engineer
Timber resources	Silviculturist
Wildlife	Wildlife Biologists
Scenery	Recreation
Aquatics	Wildlife Biologist

Several characteristics of the Pipeline problem make it interesting. Two of the more salient characteristics are an uncertain outcome of the survey and analysis and the amount of effort needed to analyze an area that is a function of several factors. Each area has unknown characteristics that may make it an unsuitable candidate for a harvesting project. Many of these remain unknown until the detailed survey and analysis has been completed. After all the work is done, you may not have a project plan that will help contribute to strategic goals. Uncertainty by itself is not enough to make this a problem, but with the addition of limited human resources (the specialists in table 1), there is a probability that you may not have enough specialized labor available to meet strategic plan goals if you do not consider the effort involved. Furthermore, even if all attempted projects are successfully planned, you still may not have completed enough to satisfy strategic goals, since actual resource amounts and availability are unknown until after survey completion. In summation, it is necessary to plan for efficient pipeline building. This plan provides one of the tactical links between strategic and project planning in the forest management planning hierarchy.

LOCAL SETTING: SCHEDULE OF ENTRY ON THE NANTAHALA AND PISGAH NATIONAL FORESTS

The 1987 forest plan began a flow of events which caused the compartment order-of-entry sequence to fail. A major cause was the new standards for timber suitability, specifically the category of lands "not suitable for timber production." On average, one-third of each compartment was no longer available to meet timber objectives. Timber suitability was designated by the USDA Forest Service definition of management areas. A new entry schedule should have been created using these units. However, even though the connection between management areas and entry schedule is clear to us today, it was not conspicuous during early plan implementation. The historic compartment entry schedule was modified to fit the new plan, but the modification didn't work well for long. Table 2 summarizes how poorly it actually did work. Over the 4-year period shown, less than 50 percent of the volume goals were achieved.

Table 2.—*Timber sale pipeline targets and accomplishments by fiscal year*

Fiscal year	Target	Attained	Percent attained
	- - - mmbf - - -		
1992	48.0	9.5	20
1993	15.0	11.1	74
1994	20.0	8.6	43
1995	10.1	5.4	54

mmbf = million board feet

At first it wasn't clear what the problem was, so a team was formed to investigate why targets were not being achieved. Table 3 summarizes the salient result of the investigation. Evidently, more than half of the cove hardwoods, and 33 percent of other types, were not available for timber production. Cove hardwoods is the most productive land type on the Nantahala and Pisgah National Forests (NPNF). More than half of the most productive land is not available for production of timber. The conclusion of the investigative team was that the spatial application of plan standards substantially reduced the available acres for timber production.

Table 3.—*Reduction in land available for timber supply by spatial factors and land type*

Factor	Cove hardwood	All other types
	- - - - - - Percent - - - - - - -	
Riparian areas	22	4
Roadbeds, nonforest inclusions, tract configuration that restricts access	22	22
Archeology sites and special habitats	2	2
Old growth standard	5	5
Total	51	33

In addition to the above problems, in 1990, former Chief of the Forest Service Dale Robertson ordered a plan revision which was to consider alternatives to clearcutting. The amendment was completed by 1994, resulting in substantial changes to the timber program. New harvest and regeneration methods, along with a more detailed plan analysis, showed that about one-quarter of the land is actually available to meet timber production goals.

This brings us to the to the spring of 1996, when the results of disjointed hierarchical planning became all too apparent. By midyear, 14 of 29 projects had been completed with more than half of the fiscal year projects still requiring analysis! Virtually all fiscal year 1997 projects were short of completion. The pipeline was almost dry. There was doubt about being able to sustain a timber sales program even at the low levels in the revised plans.

Recognizing land availability as an underlying cause, we suspected several reasons for the drop in project completion. First of all, most project efforts involved just one compartment (a remnant of the historic order-of-entry schedule), which dispersed personnel over more areas and diluted the focus of their efforts. The second suspect is the expansion of complex analysis needed to complete a timber sale. In 1988, most timber sales required about a two-page environmental assessment (EA) that was tiered to the forest plan. It is now common for an EA to be 100 pages or more. At this time it was apparent that we needed to refocus on managing the people who do the work.

AN INTEGER GOAL PROGRAMMING FORMULATION

Our goal was to develop a workable system for building timber pipeline, based on reducing the number and distribution of planning efforts and finding ways to document complex comprehensive analysis. The forest management team wanted to come as close as possible to the Pisgah/Nantahala Strategic Forest Plan ASQ each year over the next 10 years. The problem statement evolved into minimizing deviation from the ASQ set by the strategic plan, subject to the amount of human resources available to develop project plans, but it was not the final problem statement (see the section entitled "Applying the Procedure"). The formulation shown below (equations 1-7) uses a goal programming approach. Table 4 summarizes the variables used in the formulation.

$$(1)\ \text{MIN} \sum_{j=1}^{m}\left(d_j^+ + d_j^-\right)$$

$$(2)\ \text{S.T.} \sum_{i=1}^{n}\left(\text{V}_i\text{x}_{ij}\right) + \left(d_j^+ - d_j^-\right) = \text{VT [j = 1,...,m]}$$

$$(3)\ \sum_{i=1}^{n} r_i x_{ij} \le RT_j \quad \text{[j = 1,...m]}$$

$$(4)\ \sum_{i=1}^{n} b_i x_{ij} \le BT_j \quad \text{[j = 1,...,m]}$$

$$(5)\ \sum_{i=1}^{n} s_i x_{ij} \le ST_j \quad \text{[j = 1,...,m]}$$

(6) $\sum_{j=1}^{m} x_{ij} \leq 1 \quad [i = 1,...,n]$

(7) $x_{ij} = [0,1] \quad [i = 1,...n]$

[j = 1,...,m]

where:

x_{ij} = a zero/one variable. 1 if area i is entered in period j
n = number of areas
m = number of years in the tactical volume flow pipeline.
i = subscript for areas
j = subscript for year
BT_j = labor time available to survey plant life in year j
ST_j = labor time available to perform sales preparation activities in year j
RT_j = labor time available to survey and design roads in year j
r_i = labor time needed to survey and design roads in area i
b_i = labor time needed to survey plant life for area i
s_i = labor time needed for sales preparation activities in area i
d^-_j = under achievement of volume target year j
d^+_j = over achievement of volume target year j
V_i = estimated volume available in area i
VT = yearly ASQ goal.

Equation 2 is the goal constraints. There is one for each year in the planning horizon. Equations 3, 4, and 5 are the survey labor constraints, and equation 6 is the requirement that an area is entered no more than once during any 10-year period.

Table 4.—*Results of interviews with specialists: the number of days needed to perform required duties based on a site's access*

Specialists	Access		
	Easy	Medium	Poor
Silviculture	50	60	75
Archeology	20	30	40
Botany	8	20	30
Wildlife	8	14	30
Scenery	5	10	20
Aquatics	2	7	20
Engineering	4	4	8

Note that there are three categories of labor required to develop projects: plant survey, sales preparation, and road planning. These three are not necessarily the only categories nor are three separate categories necessary. Assigned tasks are interchangeable to some degree. For example, a silviculturist may be able to perform all tasks while a forest engineer may not be qualified to perform a botanical survey and a botanist may only be able to perform the botanical survey. The next section will discuss various ways of addressing the interchangeable labor problem.

PROCEDURE AND INITIAL SOLUTIONS

Using the above formulation, we wanted to develop and recommend a schedule for planning projects over the next 10-year period. Once this recommendation was developed, each district would review the schedule. Having district personnel judge the reasonableness of the schedule helps increase confidence in it. The following procedure was followed to produce the initial recommendation.

1. We subdivided the NPNF into 113 logical areas for additional study and analysis. Staff foresters call these areas "analysis areas." The term "analysis area" as used here does not have the same meaning as the "analysis area" used in forest planning. These "analysis areas" are heterogeneous, contiguous areas that represent sensible opportunities for project analysis. These areas average 8,900 acres with a range from 770 to 31,000 acres. To avoid confusion, the term "planning areas" (PA) will be used from now on instead of "analysis areas."
2. We copied the "Continuous Inventory of Stand Conditions" data base for the NPNF into a Paradox,, relational data base. A data field was added for each stand in a PA.
3. We calculated the acreage available for harvest each of the next 10 years. To do this, a series of data screens were constructed to filter out stands not suitable for harvest.
   a) The first screen was based on the early successional species (ESS) standard from the NPNF forest plan (III-29 to III-31). The acreage of allowable harvest available in each PA was calculated using this standard. Using this, the allowable acres in PA's could increase over the 10 years as stands mature.
   b) The second screen filtered out stands which did not have the minimum age for harvest. This could also increase over the 10 years as stands matured.
   c) We applied the third screen to the acres

remaining after (b). The available acres were reduced further for other standards. Riparian areas are a major example of this. A random sampling procedure established that 29 percent of "cove hardwoods" and 11 percent of other forest types were within riparian areas.

d) Finally, we compared the available acres with the maximum allowable under the ESS standard. The comparison revealed that the ESS standard was most restrictive about 90 percent of the time. Therefore, the acres available using the ESS standard was used to complete the analysis.

4. We conducted interviews with specialists on the forest to obtain estimates of time required for project planning up to the National Environmental Policy Act (NEPA) decision. We used an average timber sale of 240 acres comprised of 8 units with 30 acres in each unit. Specialists were asked to estimate the time required to complete required tasks on this average sale. We further assumed that the average sale had medium access. Table 5 summarizes the results from the interviews. The person days per acre and the acres available in a PA over the next 10 years were added to the data base. Available acres change on a year by year basis as the ESS conditions change.

5. We needed an estimate of the work force. Table 6 summarizes the estimate of available work force on the NPNF at the time of the analysis. However, a larger work force could probably be assembled if the forest could not meet strategic goals with existing specialists. We thought that other people could be reassigned to project planning. Consequently, we decided that we could reasonably expect up to 3,000 person days per year available for project planning.

6. The programming language (PAL) in the data base program Paradox" was used to write a matrix generator for the problem. We solved this problem as an integer program with the mathematical programming software ORSYS. The solution provides a schedule of entry for planning areas over the next 10 years that will minimize deviation from strategic ASQ levels.

Table 5.—*Work force calculations for potential project planning on the Nantahala and Pisgah National Forests*

Specialty	Persons	Expected days/person/year	Work days available/year
Silviculture	7	120	840
Archeology	2.33	160	373
Botany	2.5	160	400
Wildlife	2.33	160	373
Scenery	1	160	160
Aquatics	2.33	160	373
Engineering	2	160	320
Total days/year			2,839

Table 6.—*Summary of project planning schedule: number of planning areas (PA's), environmental assessments (EA's), available acres, and person days required for sales preparation by year on the Nantahala and Pisgah National Forests*

Year	PA's	EA's	Available acres	Person days
1997	14	11	3507	2727
1998	12	10	4057	3039
1999	10	10	2140	3193
2000	11	9	4160	4200
2001	10	9	4321	4018
2002	10	9	4933	4541
2003	10	9	4362	3903
2004	10	9	4485	3587
2005	88	8	4235	3183
2006	12	10	5116	3527

APPLYING THE PROCEDURE

The solution to the above problem, formulated as in equations 1 through 7, pointed out the need for new operational constraints and a major obstacle. First, even though one of the intents of this analysis was to pool labor resources over the two forests so that an efficient order-of-entry schedule could be found, the initial solution allocated an unacceptable amount of the work to one forest. Now we had a new question to answer: What is an acceptable distribution of work between the two forests? Because of issues involved, it became apparent that the only acceptable distribution was to treat each forest equally. Thus, each forest would be given an approximately equal amount of labor resources to allocate internally. Second, the major obstacle was that ASQ goals were consistently underachieved with the amount of labor available. This problem more or less negated the work allocation problem, and of course, helps explain why the pipeline was going dry in the first place. It also clearly emphasized that the forests needed additional labor resources to meet strategic goals.

A request was made to analyze this new problem. The terms were to find an efficient order for each forest with 1,500 person days available per forest. The labor constraints—equations 3, 4, and 5—were combined into a single goal equation for each forest.

$$(8)\quad \sum_{i=1}^{n} r_i x_{ij} - d_j^+ = RT_j \quad [j = 1,...m]$$

where r_i is now the labor time needed to plan area I,

RT_j is the labor time available in period j, and

d_j^+ is over use of labor period j.

The objective now was to minimize deviation from ASQ while minimizing excess labor requirements. Two new solutions—one for each forest—were developed. These solutions were then taken to each forest where district personnel evaluated solution reasonableness.

Some of the results of the timber sale pipeline are displayed in table 6. The PA and EA columns show the total number of planning areas needed to plan for the year and the least number of EA's needed. One of the major benefits, as stated by district personnel, is that by using larger PA's fewer EA's need to be written. We expect to have about one-third the amount of NEPA documents compared with current levels. In addition, adjacent planning areas scheduled in the same year may be assessed in one document. The acres available for timber harvest in the PA's are listed in the "Available Acres" column. These are an estimate of the acres available to meet timber production objectives using the ESS in the strategic plan. Using volume per acre estimates, approximately 3,000 acres per year are needed to meet plan objectives. In 1999, we will have difficulty meeting timber targets. We are scheduled to be short in accessing 860 acres, and in addition, 40 percent of the PA's are rated as high difficulty. This problem needs to be addressed further by the district personnel. The person days column exceeds the goal of 3,000 person days per year every year except 1999. However, it was one of our expectations for the new project planning schedule to more efficiently utilize human resources by focusing effort from many small to fewer large project planning efforts. Hopefully the forests can achieve this efficiency gain, reduce the number of person days required, and be within the expected labor resource. The results of this analysis will be tested over the next 10 years. Analysis estimates of the proper order of entry for project planning will be judged a success if the strategic level ASQ is satisfied with existing personnel (i.e., if the pipeline doesn't run dry). The solution contains both a quantitative element (the integer goal program) and a qualitative element (the knowledge and experience of the forest's staff). If insufficiencies are found with this solution, it is the responsibility of management to make adjustments and move to a better solution.

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USING SPATIAL STATISTICS TO LOCATE TREES WITH HIGH COMMERCIAL VALUE

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ABSTRACT.—Geostatistics is a branch of applied statistics that models and estimates spatial patterns. The distribution of trees by species and size across a region, such as a state, form a spatial pattern. Based on the species, size, and quality of the tree, a dollar value is assigned to each tree. One hypothesis is that trees of a specific dollar value are located near other trees of similar economic value. This might occur due to similar growing conditions and land use histories. Because it is impossible to sample every tree on every acre, statistical interpolation procedures are used to estimate the value of the trees between sample points. Four different procedures were used: a moving window average, ordinary kriging, indicator kriging, and sequential gaussian simulation. Each procedure is best suited for a particular set of circumstances. Of the four procedures, sequential gaussian simulation is more versatile, providing information on medians and ranges as well as the average.

INTRODUCTION

Time and cost constraints do not allow for an exhaustive inventory on a few hundred acres of forest land much less across an entire state. The alternative to an exhaustive inventory is a sample. Sample plots are selected throughout the area of interest to obtain estimates of the forest resource. All of the trees within the boundaries of the particular plot are measured. A plot total for any tree attribute is the sum of that attribute for each individual tree on the plot. In this context, these totals are point samples. However, point samples provide limited information. They do not provide information on the attribute or phenomenon of interest between the sample points. Interpolation procedures provide these estimates at unsampled locations.

Geostatistics is a branch of applied statistics that concentrates on the description of spatial patterns and estimating values at unsampled locations. The basic premise of geostatistics is that, on average, observations closer together are more similar than those farther apart. Neighboring trees share similar soils, elevation, aspect, moisture levels, and land use histories. Thus, neighboring trees should be of similar value.

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Value is a function of the species, size, and quality of the tree. Value is important to both forest planners and to timber companies. Obviously, timber companies are interested in the location of trees with a particular economic value in order to harvest and locate mills. Forest planners are also interested in the location of trees with a particular economic value for managing the forest resource. Four different procedures were compared to estimate the values of trees between sample points: a moving windows average, ordinary kriging, indicator kriging, and sequential gaussian simulation.

DATA

The data set was collected by the Northeastern Forest Inventory and Analysis (NEFIA) unit of the USDA Forest Service. The data set is from the 1989 forest inventory for Pennsylvania and is part of the Eastwide Forest Inventory Data Base. Forest inventories are designed to estimate the amount of forest area and volume within a specified statistical error. The data from these inventories can be used for other studies. The on-the-ground sample has both forest and nonforest plots. This study used 2,967 forested plots. The average distance between the plots was approximately 3 km.

The Pennsylvania Woodland Timber Market Report (1993 - 1996) gives the stumpage prices paid for pulpwood and sawtimber in the Commonwealth of Pennsylvania for each quarter of the year. Figure 1 shows the division of the state into four timber regions: Southwest (SW), Northwest (NW), Southeast (SE), and Northeast

(NE). Prices are reported for 10 species groups in each region. The timber markets within each region are unique. For example, the quality and quantity of black cherry in the NW region surpasses that in the other three regions, and is some of the most valuable black cherry in the world. The number of reporting mills varies each quarter. There is also a seasonal variation in prices. To account for these differences, an average of the stumpage prices weighted by the number of reporting mills is taken over 13 quarters. Table 1 gives the price of each of the 10 species, by region. Species that were not members of one of the 10 species groups were classified with the group having the most similar growing and competitive characteristics. Only trees larger than or equal to 5 inches in diameter at breast height (dbh) were included in this study. Value is the product of the price, net board-foot volume for the saw log portion of the tree and the net cubic-foot volume for the pulpwood portion of the tree, and any required conversion factors. The net cubic-foot volume of the tree is the difference between the gross volume and the amount of cull in the tree. Thus, the net cubic-foot volume reflects the quality of the tree.

For a saw log tree, the value of the saw logs plus the value of the pulpwood of the other parts of the tree were compared with the value of the tree as pulpwood alone. The value of the tree is the maximum of these two values. The value of a pole size tree is its pulpwood value. Each tree was weighted by its per-acre expansion factor. The value of all of the trees on a plot was summed. Figure 2 shows the location of the plots by value classes for the state. The classes are widely distributed across the state. The sampling is more intense in the NW region in the Allegeheny National Forest (ANF) than in the other regions of the state. The number of forested plots is lower in the southeastern part of the state due to the Philadelphia metropolitan area and the abundance of agricultural land. However, the volume per acre is high in this area due to low levels of harvesting. The forest land is fragmented and primarily privately owned. Yellow-poplar, northern red oak, and other oaks are the most valuable species in the SE region. This area was not as affected by the gypsy moth outbreak in the 1980's as were other parts of the state

The ANF in the NW region covers the counties of Warren, McKean, Forest, and Elk. It is managed land. Widmann (1995) states that due to the management practices, the ANF has 15 percent of its stands in the sapling-seedling class, 12 percent in the poletimber class, and 73 percent in the sawtimber class. Poletimber stands were thinned to hasten the shift of these stands into the sawtimber class. Black cherry, red maple, and sugar maple are the top sawtimber species in the ANF. Much of

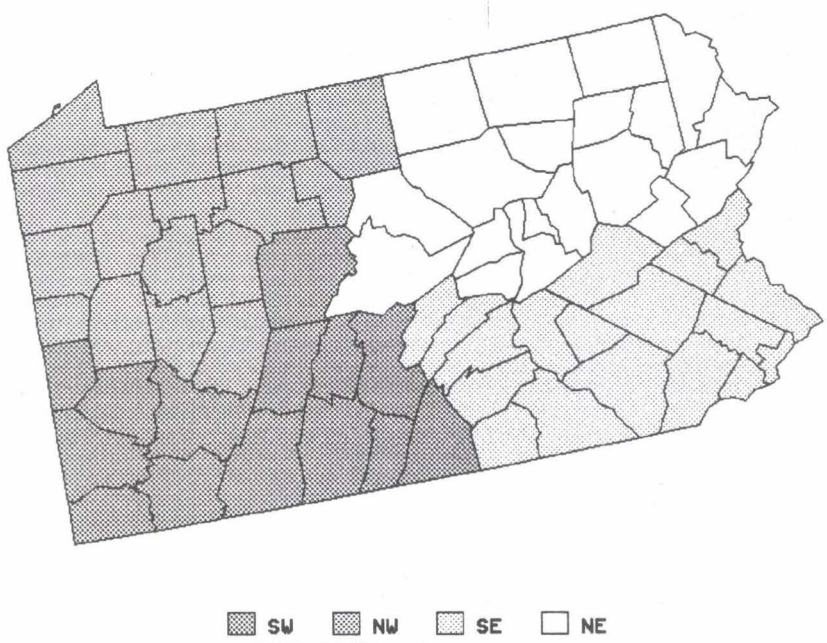

Figure 1.—*Timber regions of Pennsylvania.*

Table 1.—*Dollars/MBF by region and species*

Species Group	SW	NW	SE	NE
Northern red oak	381.74	498.13	417.94	374.00
White oak	264.68	236.68	323.40	178.97
Mixed oak	244.79	224.68	338.77	175.84
Black cherry	387.13	817.34	280.55	695.66
White ash	280.91	277.45	384.66	311.42
Hard maple	160.46	200.53	218.51	203.51
Soft maple	136.49	121.80	159.75	118.67
Yellow-poplar	170.25	112.22	220.98	125.16
Misc. hardwoods	125.61	63.09	160.31	73.36
Pine-hemlock	90.46	41.81	117.79	63.60

Figure 2.—*Spatial distribution of the species.*

the black cherry is growing in even-aged, overstocked stands, approaching 90 years of age. Black cherry, northern red oak, and red maple are the predominant species to the south and west of the ANF in the NW region.

The SW region contains the most rugged and highest mountains in the state. The mountains form a pattern of ridges and valleys that extend into the Pocono Mountains in the SE and NE regions. The steep slopes are often forested and state owned, while the valleys are agricultural areas. Although black cherry is a top sawtimber species in the far southwestern counties, the ridge and valley region is dominated by oaks. The oaks were heavily hit by drought and gypsy moth in the 1980's. This led to salvage harvesting. The Pocono region contains the major anthracite coal fields of the country. The logging and coal industry wreaked heavy damage in this region around the turn of this century. Small trees were repeatedly harvested for mine props..

Powell and Considine (1982) state that the extreme part of the NE region was glaciated. Northern hardwoods rather than oaks grow in former glaciated regions. The top sawtimber species are sugar maple, red maple, and eastern hemlock. White ash is also a predominate species in this region.

Both the activities of man and nature affect the distribution of the species. In most situations, nature provides a gradual change over the landscape, but the activities of man cause more abrupt change. This impacts the basic assumption of geostatistics that neighboring sample plots are similar. Therefore, not all of the local variation can be modeled at the current sampling intensity of the FIA plot samples.

Figure 3 shows the distribution of the plots by $500 stumpage classes in Pennsylvania. The species are heavily skewed toward the lower dollar classes. The plots in the extreme higher dollar classes are in the NW region and have large black cherry trees.

INTERPOLATION AND SIMULATION TECHNIQUES

A moving window statistic is a descriptive interpolation technique. A state or region is subdivided into windows or blocks of equal size. The size of the window should be large enough to capture several observations and produce reliable statistics, yet small enough to capture the local variation. These are conflicting goals. Usually, there is not enough data for every single window to have a sufficient number of observations and produce reliable statistics. The solution is to extend the window so that adjacent windows share some of the same data. Any descriptive statistic such as the mean, median, variance, standard deviation, and ranges can be calculated and mapped. Figures 4a and b show the moving average and variance for the valuable species in Pennsylvania. (Maps are placed together for comparison: so, the figures are not referenced in numerical sequence.) The window size was 5 km x 5 km and the search radius was 20 km.

Knowing and mapping the uncertainty of any estimate is critical before making any management decision. Are the areas of high variability due to natural variation in the phenomenon or are they due to very few observations in the region? The high variability in the ANF region is due to plots with large valuable black cherry trees being located near other plots that are less valuable. The variability in the southeastern part of the state is due to the relatively few forested plots.

Ordinary kriging, indicator kriging, and sequential gaussian simulation all require a model of spatial continuity. The tools for modeling spatial continuity are the variogram, correlogram, and covariance. Isaaks and Srivastava (1989) and Rossi *et al.* (1992, 1994) are three excellent references on variogram models. An experimental variogram models the average degree of similarity between samples as a function of the separation distance and direction. The "nonergodic" or spatial covariance model accounts for the differences in local means. The "nonergodic" correlogram filters the differences in both the local mean and the local variance. All three models are usually plotted as a function of distance alone. Both the covariance and the correlogram models may be transformed to look like variograms. Any of the three models may be used in the kriging or simulation routines. Developing a theoretical and an experimental variogram is perhaps the most critical and certainly the most time consuming aspect of geostatistics. In the first phase, an experimental variogram is built from the sample data. In the second phase, a theoretical variogram is built using linear combinations of the exponential, gaussian, and spherical functions. In kriging, there is a requirement that the system of equations be positive definite. These functions and their linear combinations meet this requirement.

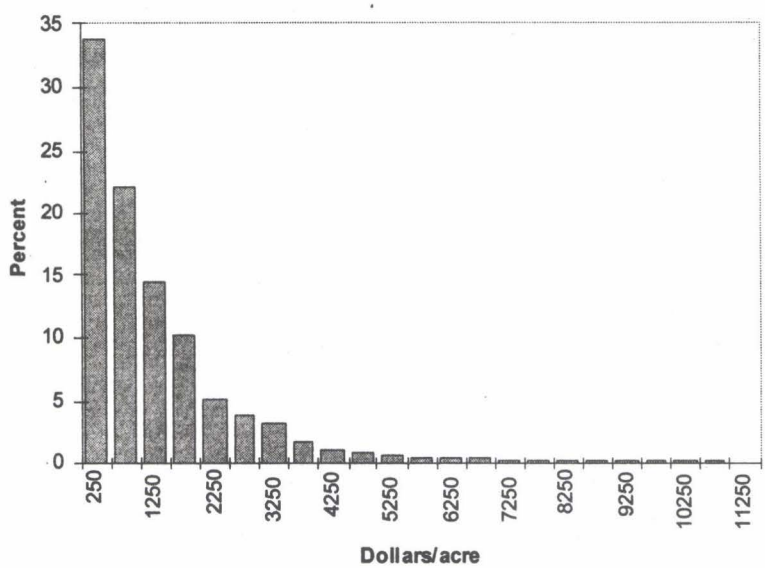

Figure 3.—*Histogram of the sample data in $500 classes.*

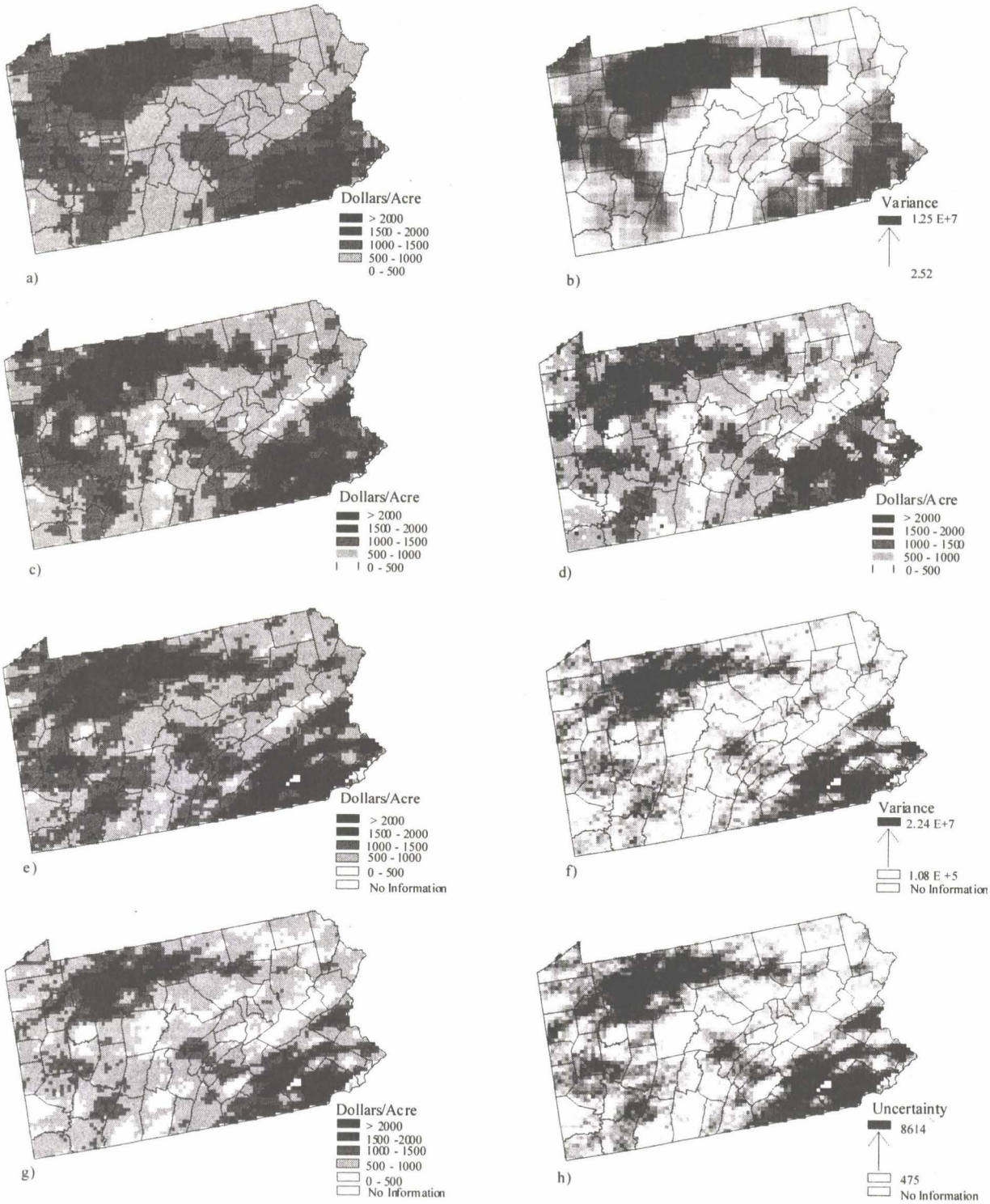

Figure 4.—*(a) Moving window mean, (b) Moving window variance, (c) Ordinary kriging, (d) Indicator kriging, (e) SGS mean, (f) SGS variance, (g) SGS Median, (h) Range of uncertainty about the median.*

Figures 5 and 6 are variograms of the value attribute for all species in the state. A variogram, covariance, or correlogram rises and then levels off at its sill. The sill is the population variance. Often as in figures 5 and 6, the variogram is standardized by dividing each variogram value by the population variance. The distance at which the variogram reaches its sill, 147 km in figure 5, is called the range. Beyond the range, the samples are no longer correlated and are independent. The intercept of the variogram on the vertical axis is called the nugget. Ideally, the nugget should be zero. A nonzero nugget indicates either sampling error or that there is spatial variability below the minimum lag, which cannot be measured with the current sampling scheme. A lag is a distance class. Correct selection of the lag is critical in variography. A good starting point is the average distance between the samples. However, many factors such as the total number and arrangement of samples, the goals of the study, and the number of pairs available at small lags affect the lag selection.

The nugget in figure 5 is 0.6. This means that 60 percent of the variability is unexplained. In practice, it is desired that the nugget be below 0.5. Still, there is enough of the spatial variability explained in the model to warrant the use of geostatistical techniques. If the variogram is constant, then using geostatistical techniques should be equivalent to a moving average procedure. Figure 6 illustrates another point. This variogram takes into account direction, whereas figure 5 is an omnidirectional variogram. The range is 232 km for the directional variogram. The difference in ranges between the two variograms indicates geometric anisotropy and must be taken into account in kriging and simulation.

All ordinary kriging (OK) routines are weighted moving averages. OK routines assign a value to a particular location or a block. The observations closer to the estimated point in both distance and direction are weighted more heavily. Rossi *et al.* (1994) states that OK

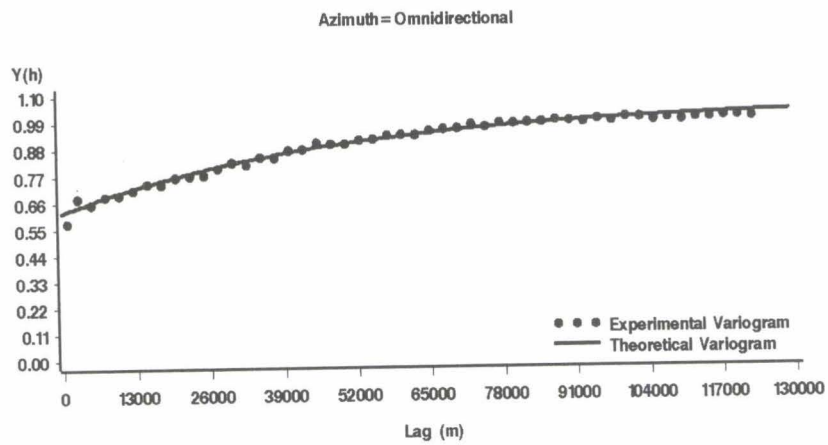

Figure 5.—*Omnidirectional variogram for all species.*

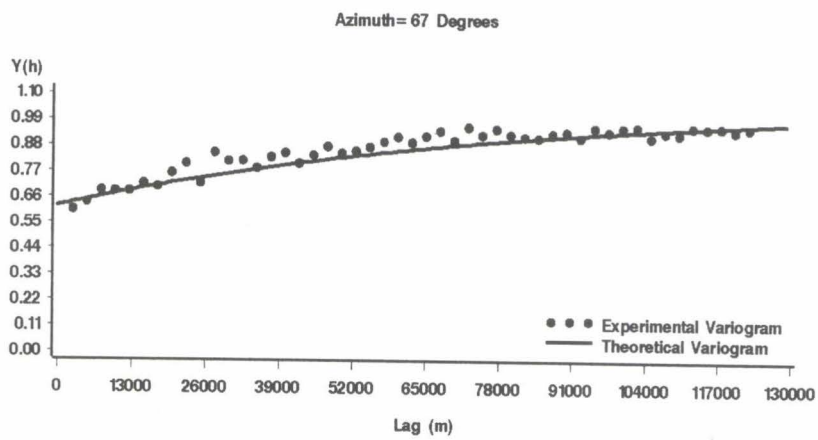

Figure 6.—*Variogram for all species - shows anisotropy.*

has three advantages over more traditional point estimation techniques such as inverse weighting, triangulation, and moving window statistics. First, OK can provide estimates, which are either higher or lower than the sample values for a specific location. Second, OK takes advantage of both distance and direction among the samples to determine its weights. Third, OK attempts to minimize the variance of the expected error. Figure 4c is the OK map for the estimated timber values in Pennsylvania. The block size is 5 km x 5 km and the search radius is 20 km. The kriging variance provided by the algorithm is, in general, independent of the data values and cannot be used as a measure of estimation accuracy. The only exception is if the data are from a multivariate normal distribution.

Indicator kriging (IK) is a variant of OK. IK divides the data set into two classes. One class is above the cutoff of interest and the other class is below that cutoff. A cutoff of interest in this project might be to model the location of trees worth more than $2,000/acre. At least 10 percent of the population must be on one side of the cutoff. IK requires a special variogram called an indicator variogram. The indicator variogram is binomial, assuming the values of 0 or 1.0 IK provides an estimate of the probability that the location's value is 0 or 1.0 IK uses either OK or another type of kriging, simple kriging (SK), to estimate the probabilities. An advantage of both IK and OK is that no specific distribution of the data is required. However, neither technique produces a variance estimate. The IK map for the valuable species in figure 4d was made by overlaying an IK map for each cutoff: 500, 1,000, 1,500, and 2,000.

Sequential Gaussian Simulation (SGS) is a stochastic conditional simulation, also known as stochastic imaging technique. Rossi *et al.* (1993) provides an excellent review of stochastic conditional simulation, sequential gaussian simulation, and indicator sequential simulation. The goal of stochastic conditional simulation is to create multiple, equally probable images of the variable or phenomenon of interest. Each image is called a realization. Each realization should recreate the "vital" statistics of the sample population, i.e., the sample data's moments. The basis of stochastic conditional simulation is Monte Carlo simulation and Bayes' theorem. SGS applies the sequential simulation procedure using the multivariate normal distribution. An assumption is made that the multivariate normal distribution accurately describes the spatial characteristics of the data. Typically, the original data are not normally distributed. The original data must be normal scored before the SGS process, and the results are then back-transformed. SGS also assumes the transformed data are multivariate normal. Bivariate normality may be checked, but multivariate normality must be assumed.

Using SGS, 200 realizations were created for the estimation of the location of trees with high commercial value in Pennsylvania. Each 5 km x 5 km block has 200 estimates of the dollars per acre of the trees in that block. These estimates form a distribution. For each block, summary statistics such as the mean, median, variance, standard deviation, and ranges are calculated and mapped. Figures 4e and 4f show the mean and variance for the location of valuable trees in Pennsylvania. Figures 4g and 4h show the median and the difference between the 84th and the 16th percentile. The difference between the two percentiles is a measure of the variability.

RESULTS AND CONCLUSIONS

All of the procedures show the same large-scale trend. The trees of high commercial value are in southeastern Pennsylvania and in the ANF region. The ridge and valley area has trees of lower commercial value. These results correspond to the land use and species distributions as previously discussed.

All of the procedures smooth the data. In any smoothing process, the high-population values are underestimated and the low-population values are overestimated. The goal for the moving windows average, OK, and SGS mean is to be correct on average. IK has a different objective. IK attempts to retain the same proportion of estimated data points above and below each cutoff as in the original data. Table 2 compares the descriptive statistics for the interpolation procedures with the original data. The mean of the 200 SGS realizations, 1,299.36, is closest to the mean of the original data, 1,289.05. A comparison of the moments illustrates the smoothing. OK detects more extreme values than SGS mean. Another way to compare the procedures is to use the block estimates for each procedure as input for an experimental variogram. These new experimental variograms are compared with the original experimental variogram in figure 7. A single realization of the SGS procedure best reproduces the original variogram. Unfortunately, a single realization is only one possible picture. Many realizations are required before any level of uncertainty can be assigned to each block. SGS mean and OK equally re-created the original variogram. Due to the smoothing, it was not expected that any of the procedures would closely re-create the variogram of the original data. The ultimate test in comparing the procedures is to examine the maps. The moving average map is more smoothed than the maps from OK and SGS mean. However, the map captures the major trends and does not require any variography. An estimate of the variance is also available. Both OK and SGS require variography, which is time consuming. SGS is more computer intensive than OK, requiring more temporary storage space and computation time. However, with today's computers these are not significant factors in

dismissing SGS. SGS produces a variance and other output statistics. OK only gives an average. From the maps in figures 4c and 4e, SGS maintains more local variability than OK. SGS detected the absence of forested plots in Philadelphia County and in the center of Lancaster County. Thus SGS is the better procedure. Riemann Hershey *et al.* (1997) also concluded that SGS was superior to OK and multigaussian kriging in their study of tree species distribution in Pennsylvania.

Table 2.—*Comparison statistics for the original data and the averaging techniques*

	Original data	Moving average	OK	SGS mean
Mean	1289.09	1234.87	1235.33	1299.36
Skew	3.03	1.62	1.84	1.76
Variance	2218370	393941	481590	478747
CV	115.54	50.83	56.18	53.25
Maximum	19088.31	4746.73	6631.79	6484.76
Q3	1707.35	1474.78	1540.46	1529.37
Medium	843.79	1082.29	1062.01	1115.56
Q1	339.00	800.43	757.74	833.67
Minimum	0.00	7.76	6.48	254.08

Both the IK map and the SGS median map provide different views of the phenomenon. In appearance, these two maps are more closely related than the maps for SGS mean, OK, and the moving window average. The maps are not as smoothed. The far western counties receive a lower estimate with these procedures. Rossi *et al.* (1993) state that when the conditional probability distribution at each simulation point is not normal or symmetric, a more robust statistic is the SGS median. The ultimate decision on which map is better rest with the user and his or her objectives in using the map.

The current maps do not differentiate between the trees of high commercial value in the ANF and in southeastern Pennsylvania. One area is heavily forested and the other area is sparsely forested. The interpolation procedures assign values to areas that are not forested. One solution is to overlay in a GIS the map of trees of high commercial value with a kriged map of the forest/nonforest areas. The forest/nonforest map could be from the FIA photo interpretation points or from satellite imagery such as Landsat Thematic Mapper (TM) or Advanced Very High Resolution Radiometer (AVHRR). The FIA photo interpretation points are at a finer scale than the on-the-ground sample data. The nonforest locations are then masked. This map would provide a more useful decision tool.

There is enough spatial structure to support the hypothesis that trees of a specific economic value are located near other trees of similar economic value. The maps make sense. The results would be locally more accurate if data were available at a smaller scale.

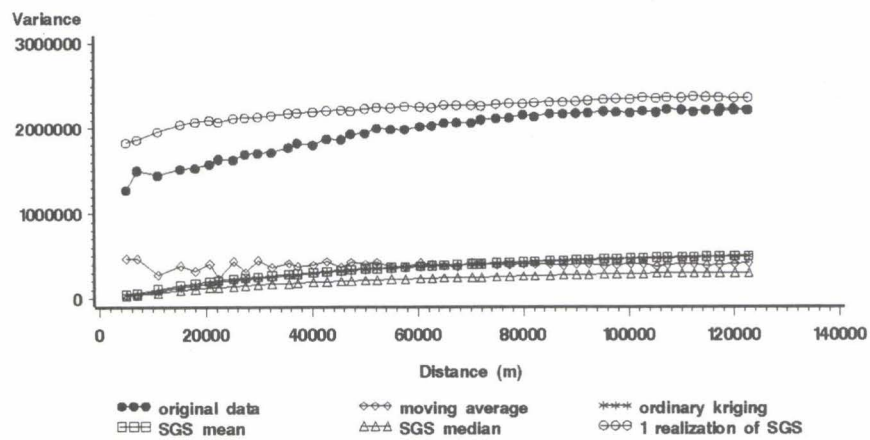

Figure 7.—*Comparison of variograms from estimated data sets.*

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ADDRESSING ENVIRONMENTAL CONCERNS IN FOREST MANAGEMENT MODELS[1]

J.G. Borges and H.M. Hoganson[2]

ABSTRACT.— There is an increasing awareness of the value of forests for wildlife and biodiversity protection, recreational uses and aesthetics. The effort to supply wood in order to satisfy the demand of timber related products is increasingly constrained by spatial considerations—how to layout the harvests in order to account for other demands from the forests. The spatial arrangement of harvests has become a critical environmental concern. Nevertheless, modeling spatial aspects of forest management remains a challenging problem. A modeling approach to spatial constraints in forest management will be discussed. Preliminary results will be presented. The spatial conditions generated by the model may be viewed as an output of the forest. The potential to assess the impact of adjacency constraints on these forest spatial conditions will be addressed.

INTRODUCTION

Research on quantitative modeling of forest management scheduling has traditionally evolved within a strategic management framework (Covington *et al.* 1988). Strategic models usually aggregate stands because of computational constraints and lack spatial resolution (Nelson *et al.* 1991). However, the implementation of forest plans requires spatially feasible prescriptions. Detailed forest inventories, the development of GIS technology and prior research efforts provided the integrated functionality of available software tools and a solid base for harvest spatial design analysis. Nevertheless, modeling spatial aspects of forest management remains a challenging problem.

Heuristic techniques based on the decomposition of a linear programming (LP) master problem such as the ones developed by Hoganson and Rose (1984) and Lappi (1992) avoid stands aggregation and have the ability to recognize considerable spatial and inventory detail within a strategic planning framework. Nevertheless, the demand of non-timber outputs impacts the opportunity set for harvest scheduling alternatives. In addition to the ability to recognize individual stands in the output of a harvest scheduling model managers must take into account the interactions between management decisions in neighboring stands. The spatial conditions generated by a model (e.g., amount and type of forest edge and interior space) become an additional forest output.

The issue of spatial relationships analysis within forest management models has been addressed in recent research work. The integration of adjacency constraints in the process of forest management model building and solving has received considerable attention (e.g., Nelson *et al.* 1991, Weintraub *et al.* 1994, Murray and Church 1995, Snyder and ReVelle 1996). Nevertheless, the large-scale attributes of most forest management problems complicate significantly the process of model solving.

The research presented in this paper focused on the development and application of a technique to solve forest management problems with adjacency constraints. These involve the definition of an exclusion period: the number of planning periods that must elapse between the implementation of two similar management actions in any two adjacent stands. Hoganson *et al.* (1994) and Borges *et al.* (1994) have showed that a dynamic programming based heuristic may circumvent computational constraints to solving this particular combinatorial optimization problem. In this paper, further research developments are presented.

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THE DYNAMIC PROGRAMMING MODEL FORMULATION

Adjacency constraints may be formulated as sums of binary variables (their values being either 0 or 1). Each of these represents a decision to be made in a stand in a particular planning period. If an activity is scheduled to be implemented in a stand at a given period, the corresponding variable will take the value 1; otherwise, its value will be 0. By constraining the sum to take a value less or equal than one, it is ensured that no conflicting activities are developed in adjacent stands. The solution of the adjacency problem consists in assigning adequate values to all binary variables: it is a combinatorial optimization problem.

Reeves (1993) classified combinatorial optimization techniques into two groups. The first includes operation research models that enable finding an optimal solution to the problem. The second includes the heuristics, which seek to approximate an optimal solution at a reasonable computational cost, without being able to guarantee optimality or even feasibility. Dynamic programming (DP) is included in the group of the former methods. Nevertheless, the technique presented by Hoganson *et al.* (1994) combines characteristics of both DP and heuristics. A DP model is used to find optimal solutions of subproblems resulting from the decomposition of a master forest management problem. These solutions are combined in order to approximate optimal solutions to the master problem, like an heuristic, but in such a way that if not optimality, at least feasibility is guaranteed; that is, forest management schedules comply with the adjacency constraints included in the model.

Hoganson *et al.* (1994) described the key elements of the DP formulation. A stage corresponds to a stand. The DP network consists of arcs that represent management decisions to be made at any particular stage (stand) and of nodes, characterized by decisions made in "unscheduled stands", that is, in stands which still have adjacency relations with stands to include later in the network. The "unscheduled" stands define the "front," that is, the state variables needed at any particular stage. The size of the "front" is variable. Nevertheless, the number of nodes will not grow exponentially because there is no need to carry information about management decisions made in "scheduled" stands, that is, in stands which do not have adjacency relations with management units to include later in the network. However, in large problems, computational constraints preclude the possibility of including all stands in the forest in a single DP network. The problem must be decomposed. For that purpose, a procedure is designed to select stands to include in any particular subproblem (DP network). The subproblems are solved sequentially and the optimal solutions to the ones solved first constrain the space of feasible solutions of the ones to solve later. Hoganson *et al.* (1994) considered a rectangular grid of stands and described the approach in terms of 5 basic steps:

1. Starting along one edge of the forest, consider a large strip of the forest that would result in a DP network that is of manageable size.

2. Formulate and solve the DP formulation assuming the only stands in the forest are the stands within the strip (window).

3. If the entire forest has been included in a DP window, then all stands yet to be scheduled can be scheduled according to the optimal DP solution found in step 2. Otherwise, for stands along the outside edge of the strip (subproblem) in step 2, schedule those stands according to optimal DP solution determined.

4. Redefine the strip by: (a) eliminating from the latest strip, all stands scheduled in step 3, and (b) adding to the strip, a set of stands adjacent to the strip that have not yet been analyzed.

5. Return to step 2.

THE NETWORK DEFINITION

The order in which stands are sequenced in the DP network influences model size. This in turn determines the number of subproblems that must be considered when decomposing the master problem. Formulating the DP efficiently is further complicated when irregular shaped stands are considered. The approach to network definition may be summarized as follows:

1. Select the first stage polygon, according to its geographical position and to the direction of the window which encompasses all stands to include in a network moves. This stand will define the first front if it has adjacencies to include later in the subproblem.

2. Check stands adjacent to first stage polygon (first front). If number of nodes is lower than predefined limit then assign the second stage to adjacent stand according to geographical coordinate and to the direction the window moves. Else, assign the second stage to adjacent stand that minimizes number of states and number of stands in front in second stage. If both stands have adjacencies to include later in the subproblem, they will define the new front. Otherwise, the front will remain either with one of those two stands or, if both have no more adjacencies in the window, a new polygon is selected using the same criteria used for the first.

3. In general, in any given stage, check all polygons adjacent to all stands in the current front, and proceed as in 2. If no stands meet the requirement that the number of states does not exceed the computational limit, the network is redesigned, and the front is adjusted according to the new adjacency relations.

4. After all stands in the window have been assigned a stage number, solve the dynamic programming problem. An optimal solution to the spatially constrained subproblem is obtained. This solution constrains the space of feasible solutions of the subsequent network, which is in turn formulated using the procedure just defined. Overlapping of windows may be considered.

5. The suboptimal solution to the forest management problem is achieved when the moving window has covered the whole forest area.

APPLYING THE DYNAMIC PROGRAMMING BASED HEURISTIC

Results reported by Hoganson *et al.* (1994) and by Borges *et al.* (1994) showed that the DP based heuristic was able to confront the large-scale characteristics of forest management scheduling problems. Moreover, it was shown that, in the case of regular shaped stands, this heuristic compared favorably to methods such as Monte Carlo Integer Programming (MCIP) or Column Generation Algorithm (CGA): adjacency costs were consistently lower when using the DP based heuristic. Finally, they suggested testing further case studies and other research topics.

Up to 20 hypothetical forests with irregular shaped stands were used to test the heuristic performance. Minnesota Forest Inventory Analysis (FIA) and Department of Natural Resources (DNR) plots provided the inventory data. The Decision Support System developed at the University of Minnesota provided the management data needed. Map shells were generated so that the impact of different polygon initial area ratios on the heuristics performance might be assessed. Alternative methods were used to design management units boundaries and to split polygons that exceed a predefined maximum area. Different sets of prices were considered in order to assess the impact of sustainable flow constraints on adjacency costs. The number of stands in each forest ranged from 800 to 3,215. Planning horizons ranged from five to eight 10-year periods. The number of management alternative types ranged from 8 to 19.

Model performance has been promising. Preliminary results showed that the DP approach still easily outperformed the CGA approach and greatly outperformed the MCIP approach (Hoganson *et al.* 1996). In this paper, preliminary data from one of the case studies will be reported in order to highlight some key results obtained. These relate to the heuristic's efficiency and effectiveness. The cost of adjacency constraints and the impact of window size on the solutions will be used to assess the former. The impact of starting outside edge on the solution process will be used to assess the latter.

The hypothetical forest considered here comprised 2,954 irregular shaped stands and extended over an area of 28,156 ha. Most stands were mature: only 147 had an age lower than 30 years. The average number of adjacencies per stand was approximately five. The planning horizon over which the possibility of adjacency conflicts was considered extended over 50 years (five 10-year periods). The selection of prescriptions for each stand was made according to the potential management spatial conflicts. In this analysis, two alternative exclusion periods were considered. In the first case, the minimum period to elapse between the clearcut of adjacent stands was 10 years. In the second, 20 years. In this framework, prescriptions available for each stand were classified according to the timing of clearcuts, if any, into seven groups—prescriptions involving a clearcut in period 1, period 2,..., period 5, involving two clearcuts, in periods 1 and 5, and, finally, involving no clearcuts during the area based-planning horizon. Afterwards, the maximum Soil Expectation Value (SEV) management alternatives were selected from each group for analysis purposes. Therefore, there were at most seven management options for any particular stand. In this case study, 1,600 stands could be managed using at least six options; for the remaining 1,354 stands there were at least four management options available.

Cost of Adjacency Constraints

The cost of adjacency constraints may be computed by comparing the solutions of both the spatially constrained and the spatially unconstrained problems. The solution of the unconstrained problem may be estimated by adding the financial returns associated with the best management option for each stand. Figure 1 displays the adjacency constraints costs per hectare when no window overlay is considered. E, W, S, and N in the figure represent, respectively, the eastern, western, southern and northern borders of the forest—four starting outside edges were considered.

In the case of the one-period exclusion, adjacency costs varied from $29 to $35 per hectare in the case of the DP approach. In the case of the two-period exclusion, they ranged from $122 to $131 per hectare. The DP heuristic outperformed greatly the MCIP approach: best MCIP results, from a sample with size n = 2954, were $61 and $206 per hectare, for, respectively, the one-period and the two-period exclusions. The CGA results were closer to

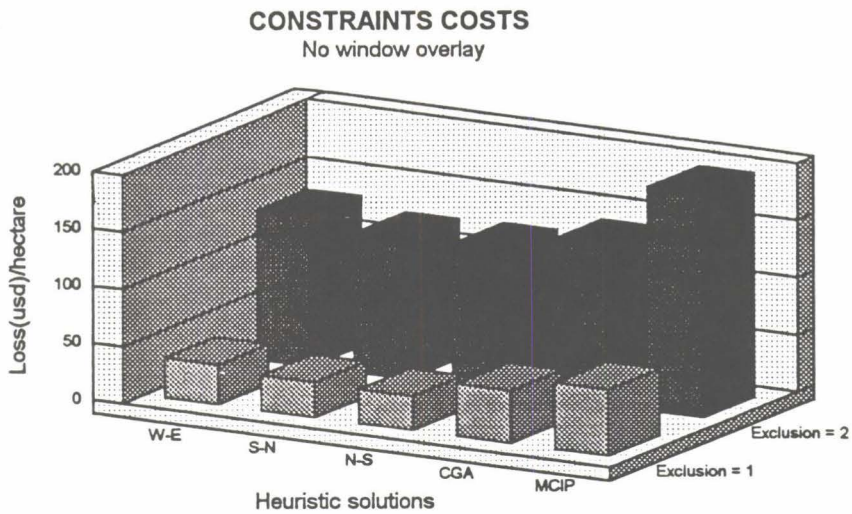

Figure 1.—*Cost of adjacency constraints (no window overlay).*

the DP heuristics': $31 and $123 per hectare for, respectively, the one-period and the two-period exclusions. Nevertheless, results also showed that increasing the window overlay contributed to reduced adjacency costs. In the case of the 75 percent overlay (fig. 2), adjacency costs were reduced to $23 and $105 per hectare for, respectively the one-period and the two-period exclusions: the DP approach outperformed the CGA method.

The efficiency of the DP approach may be further assessed by checking how larger window overlays or larger window sizes impact adjacency costs. The results displayed in figures 1 and 2 were obtained when an average window size of 4,000 ha was considered (N-S and S-N directions). Decreasing that size led to higher costs (up to $109 in the case of the 75 percent overlay and two-period exclusion). Increasing it did not affect the solution, which suggests that the window size considered was close to optimal. On the other hand, marginal gains resulting from increasing the window overlay successively from 75 to 90 percent and 95 percent were small (less than $1 per hectare) and decreasing which suggests that the solution may be close to optimal.

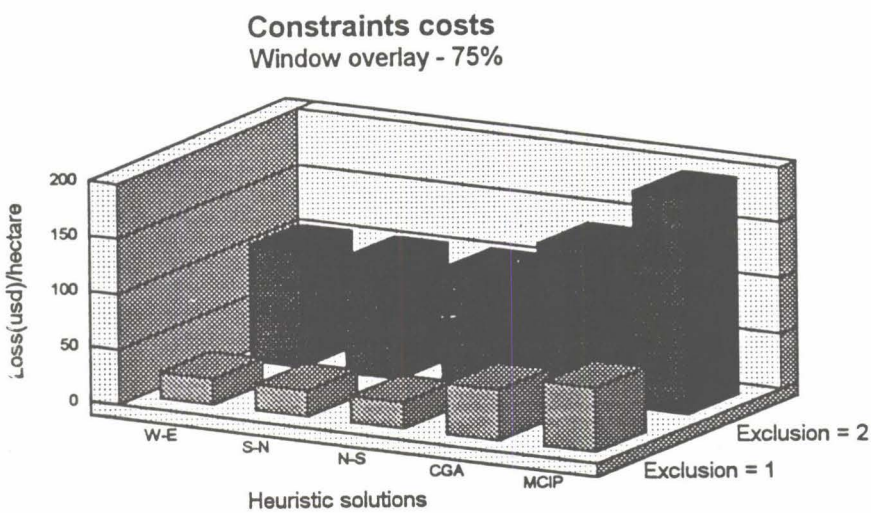

Figure 2.—*Cost of adjacency constraints (window overlay: 75 percent).*

Given that computational constraints preclude the possibility of using mathematical programming techniques to solve this combinatorial optimization problem, finding a bound to the DP approach solutions is not straightforward. The solutions asymptotic behavior when window overlay and size are increased suggests that the heuristic is getting closer to that bound. Nevertheless, an alternative method was devised in order to get an approximation of that bound. Management options dropped because of adjacency conflicts when successive subproblems of a given master problem are solved were eliminated from original input files. The value of the optimal path of the master problem obtained using the DP approach is the spatially constrained optimal solution to a problem without the management options (and respective adjacency constraints) just referred to. Therefore, by solving this new problem, it is possible to approximate the true bound to the DP solution. Preliminary results show that in the case of this hypothetical forest, deviations from the spatially constrained optimal solution might be lower than 10 cents per hectare: the DP approach solutions are close to optimal.

Impact of Starting Outside Edge on DP Solution

For all window overlays, independent runs of the model were completed starting on each of the four forest outside edges (E, W, N and S). The effectiveness of the approach may be assessed by checking if the solutions are insensitive to the outside edge on which the process of network definition is started. That was the case when larger window overlays were considered. In the case of the 90 percent overlay and one-period exclusion solution differences were lower than 40 cents per hectare. Moreover, the same management type was chosen irrespective of the starting outside edge in the case of 1,948 stands. The number of stands where solutions from three starting outside edges match increases to 2,646. The proximity to the bound on the optimal solution suggests that there is a substantial number of feasible solutions close to the lowest- cost solution found.

Computation Costs

All problems were solved using 90 MHz Pentiums and Microsoft Professional Basic v. 7.1. Computation costs ranged from about 1,100 seconds in the case of no window overlay to about 18,600 seconds in the case of a 95 percent overlay. It took about 9,000 seconds to execute the 2,954 MCIP program runs. In the case of the CGA, computation costs ranged approximately from 13,700 to 17, 400 seconds. Gains may be achieved by more efficient coding. In any case, the computational costs incurred in seeking optimal solutions appear to be reasonable

Spatial Conditions

Conditions such as the amount and type of forest edge and interior space may be analyzed in order to address environmental concerns such as wildlife habitat quality, aesthetics,... Accordingly, these spatial conditions may be interpreted as an output from the harvest scheduling model. Preliminary results suggest that adjacency costs are not very sensitive to the method used to design management units boundaries. Therefore, it appears that when designing these boundaries, environmental concerns should be emphasized. Moreover, these results show that spatial conditions vary significantly over time, even when adjacency constraints are imposed (Hoganson *et al.* 1996). This suggests that it may be interesting to assess the impact of relaxing some adjacency constraints in order to meet target spatial conditions. As Hoganson *et al.* (1996) pointed out, the DP approach enables a trade-off analysis between timber production and spatial outputs.

SUMMARY AND CONCLUSIONS

Research on forest management quantitative modeling plays an important role in providing information needed by decisionmakers to address current environmental issues. Policy requirements such as the definition of maximum clearcut openings and minimum exclusion periods complicate greatly the modeling process. Meeting target spatial conditions further complicates this process. The dynamic programming based heuristic can be used to solve large scale problems incorporating adjacency constraints defined to meet policy requirements such as the ones mentioned above. Solutions appear to be close to the optimum and computation costs are reasonable. Moreover, it may be used to assess the trade-offs between timber production and spatial conditions targeted because of wildlife habitat, aesthetics, and other non-timber forest output objectives. Thus, it may contribute to the understanding of the complex ecological and economic relationships within the framework of forest management scheduling, and to avoiding *a priori* decisions due to lack of knowledge of these interactions.

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THE DESIGN OF A GENETIC ALGORITHM BASED SPATIALLY CONSTRAINED TIMBER HARVEST SCHEDULING MODEL

David S. Mullen and Ralph M. Butler [1]

ABSTRACT.—This paper presents the design of a spatially constrained harvest scheduling model that uses a genetic algorithm (GA) as the optimization technique. The GA manipulates a population of permutations of the identification numbers of the stands being scheduled. The evaluation function of the GA uses the permutations as ordered lists providing the order by which to place stands into the schedule. Stands are placed into the schedule by an heuristic scheduling algorithm. In timed test runs, the GA based model found solutions averaging 3.5 percent better than a Monte Carlo integer programming based model.

INTRODUCTION

A large scale operational harvest scheduling problem might contain more than a thousand timber stands, span a planning horizon of 15 or more periods, include minimum and maximum restrictions on wood flow by period, and have spatial green-up restrictions of one to several periods. Problems such as this are difficult combinatorial optimization problems to which a wide variety of optimization techniques have been applied (Brodie and Sessions 1991, Lockwood and Moore 1993, Murray and Church 1994). Genetic algorithms are a class of optimization techniques that have been applied successfully to a number of other difficult scheduling problems (Davis 1991, Fang 1992, Bierwirth 1995). This paper presents the design of a spatially constrained harvest schedule optimization model[2] that uses a combination of an order-based genetic algorithm and an heuristic scheduling algorithm as the optimization techniques.

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[2] *The model presented in this paper, and two other models—a Monte-Carlo integer programming model and a traditional genetic algorithm model—were developed for the Mullen's master's thesis (Mullen 1996).*

BACKGROUND

A wide range of optimization techniques have been applied to spatially constrained harvest schedule optimization. Following are some background notes on some of these techniques.

Mathematical Programming Techniques

Both linear programming (LP) and mixed integer programming (MIP) have shortcomings when applied to large scale spatially constrained harvest scheduling. The main problem with LP is that solutions usually have some stands split among management regimes. This makes interpretation of the results difficult in terms of meeting the spatial restrictions (O'Hara *et al.* 1989). Because of this shortcoming, LP (by itself) has been largely abandoned for scheduling with spatial constraints. MIP is similar to LP, but allows constraint of some of the variables so they may only take on integer values. Using MIP with integer [0,1] variables for the management regime decision variables overcomes LP's fractionalization problem. Unfortunately, MIP based harvest scheduling models with spatial restrictions exhibit combinatorial explosion—as the number of stands increases, the computer time needed to find the optimum solution grows exponentially. This renders MIP generally unsuitable for large scale problems (Weintraub *et al.* 1994; Yoshimoto *et al.* 1994). Another problem with both LP and MIP is that it is difficult to formulate problems in a way that allows adjacent stands to be grouped together into areas that can be scheduled as a single opening. Attempts to do this for large scale problems would yield

an astronomical number of constraints, far beyond the capability of current MIP solvers (Jones *et al.* 1991).

Stochastic Optimization Techniques

Because of the drawbacks of LP and MIP, modelers have turned to stochastic optimization techniques such as Monte Carlo integer programming (MCIP), simulated annealing (SA), tabu search (TS), and genetic algorithms (GA). Nelson *et al.* (1988), O'Hara *et al.* (1989), Dallain (1989), Jamnick and Walters (1991), and Mullen (1996) all developed models that use MCIP. A problem with MCIP is that the work done to generate each solution is completely discarded before starting on the next solution. SA, TS, and GA all overcome this problem to a degree by implementing some way of remembering work done on previous solutions, and attempting to gradually improve the best solution as model execution proceeds. Lockwood and Moore (1993), and Murray and Church (1994) developed SA based models. Murray and Church (1994) and Misund *et al.* (1995) developed models that employ TS. Mullen (1996) developed two models that use GA.

Random Ordering Heuristic

Yoshimoto *et al.* (1994) developed a stochastic optimization model that used a heuristic they termed Random Ordering Heuristic Optimization (ROHO). The basic idea of ROHO is to randomly create a permutation of the stand numbers of the stands to be scheduled and pass the permutation to a scheduling algorithm that uses it as a priority list by which to place stands into the harvest schedule. The first stand on the list is placed first, the second is placed second, and so on. The model presented in this paper uses the ROHO concept. It maintains a "population" of permutations; manipulates the permutations by applying genetic algorithm selection, mutation and crossover operations; and feeds the permutations to an heuristic scheduling algorithm that evaluates their fitness.

Genetic Algorithms

Genetic algorithms are optimization heuristics that are used to search for good solutions to complex problems. They manipulate populations of strings of symbols. The strings of symbols are referred to as chromosomes. In some genetic algorithms, problem solutions are represented directly on the chromosomes. In others, the chromosomes must be transformed into the solution by the evaluation function. Genetic algorithms were developed by John Holland in the early '70s. Since that time, a large amount of research activity and practical problem solving has been conducted using genetic algorithms. This activity has applied genetic algorithms to a wide range of optimization problems, developed many new approaches to their use, and further refined the theory of how and why genetic algorithms work (Davis 1991, Beasley *et al.* 1995a, b).

Figure 1 gives an outline of a generalized genetic algorithm as given by Davis (1991). As a genetic algorithm runs, the operations performed on the population of chromosomes guide it toward better and better solutions to the problem. Figure 2 shows the evaluation results of running a particular genetic algorithm two times for a given input. It shows the value of the best solution found so far at each iteration. As is typical of most genetic algorithm results, figure 2 shows a period of rapid solution improvement in the early generations, followed by gradually decreasing improvements, followed by a plateau in which improvements are rare and relatively insignificant. Since genetic algorithms are most often used for intractable problems, the user may never know how close a given solution is to the true optimum. Further discussion of the background of genetic algorithms is beyond the scope of this paper. The interested reader is referred to The Handbook of Genetic Algorithms by Davis (1991), which provides an excellent introduction to the topic. Also, a large volume of genetic algorithm information and research literature is available on the Internet and can be located by searching for "genetic algorithms"

Step 1.	Initialize a population of chromosomes.
Step 2.	Evaluate each chromosome in the population.
Step 3.	Create new chromosomes by mating current chromosomes; apply mutation and recombination as the parent chromosomes mate.
Step 4.	Delete members of the population to make room for the new chromosomes.
Step 5.	Evaluate the new chromosomes and insert them into the population.
Step 6.	If time is up, stop and return the best chromosome; if not, go to Step 3.

Figure 1.—*General genetic algorithm.*

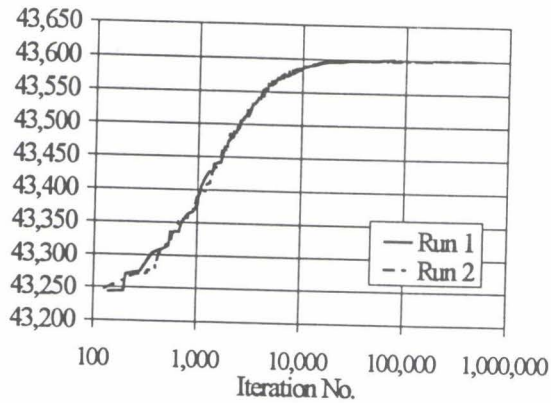

Figure 2.—*Typical genetic algorithm progress toward optimum solution.*

MODEL DESIGN

The genetic algorithm based spatially constrained harvest scheduling model presented here will be referred to as hsGAo. "hs" is for harvest scheduler, "GA" is for genetic algorithm, and "o" is added because the genetic algorithm is an order-based implementation. To present the design of hsGAo, we will discuss the following topics: harvest scheduling problem formulation, hsGAo model overview, chromosome representation, chromosome initialization, genetic algorithm operators, and the evaluation function.

Harvest Scheduling Problem Formulation

The harvest scheduling problem for the hsGAo model is defined as follows. There are N stands to be scheduled. The planning horizon is composed of a consecutive sequence of P L-year periods, numbered 1, 2, . . ., P. The total planning horizon length is PL years. There are $M = P + 1$ management regimes. Regimes 1 through P each have only one harvest and it occurs in the period matching the regime number. Regime M is the "do-nothing" regime which does not have a harvest in the planning horizon. Let E be the exclusion period or (green-up period) specified as a number of planning horizon periods. For example, if the $L = 4$ and the green-up time is 10 years, then E = CEILING(10/4) = 3. Let O be the maximum allowed opening size. Let ADJ_i be the adjacency list for stand i. Let A_i be the land area of stand i. To prevent opening size violations, stands must be defined such that for every stand, $A_i \leq O$. Let V_{ij} be the volume available for harvest from stand i in period j if managed by regime j, $j \epsilon [1,P]$. Let D_{ij} be the net present value (NPV) of stand i if scheduled by regime j, $j \epsilon [1,M]$. Let S_i be the regime assigned to stand i by the scheduling process. $S_i \epsilon [1,M]$. Note that if $S_i \epsilon [1, P]$, then it also indicates the period of harvest. A harvest schedule, then, is $\boldsymbol{S} = <S_1, S_2, \ldots, S_N>$. Let S^+_i be the unrestricted optimum regime number for stand i. That is, $S^+_i = j$' such that D_{ij}' $\geq D_{ij}$, $\forall\, j \epsilon [1,M]$. Let R_i be the implied planning period number that stand i was most recently harvested in the past. For a given stand, $R_i = 1\text{-}x$, where x is the number of periods prior to the first planning horizon period that stand i was last cut. The R_i values are used to constrain harvest of stands adjacent to recently harvested stands. Let $VMAX_j$ and $VMIN_j$ be the maximum and minimum allowed harvest volume in schedule period j. Let $VSUM_j$ be the sum of scheduled harvest volume in schedule period j, $j \epsilon [1,P]$. Let Z be the value penalty per unit of volume to be applied to period volume restriction violations. Let G_{ik} be any group (set) of adjacent stands, including stand i, that at some time during the planning horizon are considered a contiguous opening. Let A_{Gik} be the total land area of the stands that form group G_{ik}. Let T be the set of all G_{ik} found for a particular schedule. Let Z_{VMIN} be the value penalty due to violations of period minimum volume restrictions.

The spatially constrained harvest schedule optimization problem is specified by the following formulation:

Maximize:

$$(1) \qquad Q = \left(\sum_{i=1}^{N} D_{isi}\right) - Z_{\text{VMIN}}$$

subject to:

$$(2) \qquad S_i \epsilon [1,\ M] \forall\ \ i \epsilon [1,N]$$

$$(3) \qquad \sum_{i:Si=j} V_{ij} \leq VMAX\, j \forall\ \ j \epsilon [1,P]$$

$$(4) \qquad AGik \leq O,\ \forall\, Gik \epsilon T$$

The objective function, Q, shown in equation (1) is simply the sum of the NPVs of the stands as scheduled minus a penalty term for the minimum volume constraint violation. Constraint (2) forces the schedule regime, S_i, to be a valid regime number for each stand. Constraint (3) enforces the maximum volume restrictions. Constraint (4) enforces the opening size (adjacency) constraints. The constraint states that openings over a maximum allowable size (O) are never allowed to occur.

hsGAo Model Overview

Figure 3 is a high level data flow diagram for the hsGAo model. When the program starts, the initialization routine reads the problem specification inputs and initializes memory objects that contain the GA options, harvest scheduling options, harvest scheduling data, and the population of order-based chromosomes. After initialization, processing control is passed to the GA driver routines which run the genetic algorithm. The GA driver

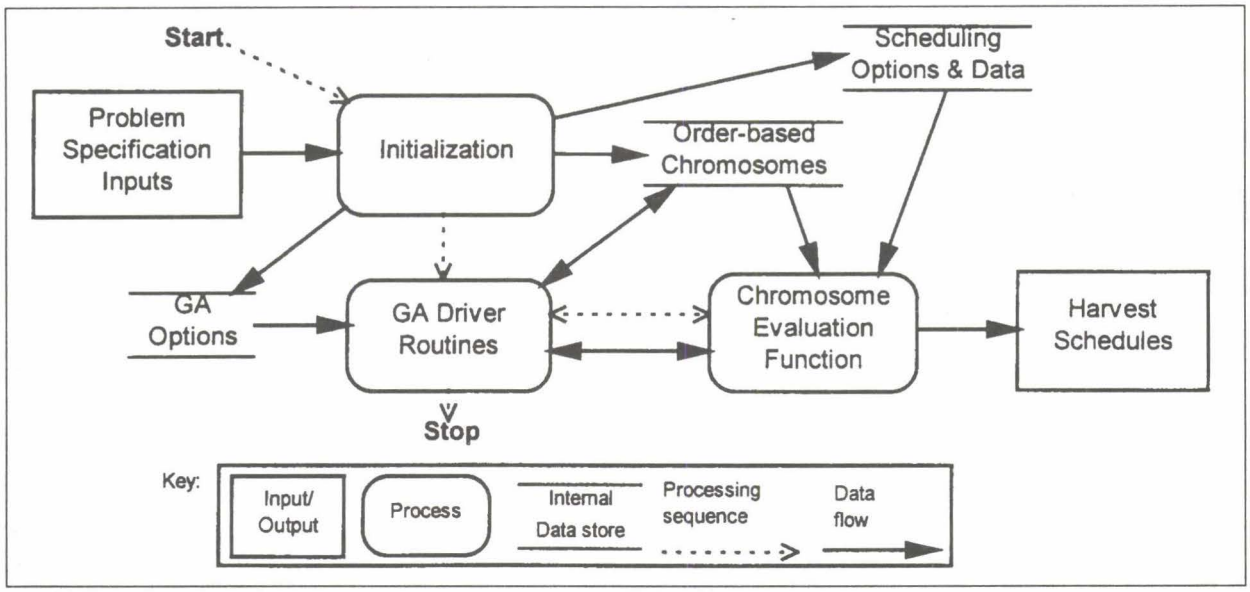

Figure 3.—*High level data flow daigram for the hsGAo model.*

routines call the chromosome evaluation function each time a new chromosome is created. The evaluation function obtains the chromosome to be evaluated; generates a harvest schedule subject to (2), (3), and (4); evaluates the harvest schedule using (1); and passes the evaluation back to the GA driver. Each time the evaluation function finds a harvest schedule that has a better value than all previous schedules, it outputs it to the schedule output file.

Chromosome Representation

In the hsGAo model, each chromosome is a permutation of the list of stand numbers that are being scheduled. If there are N stands being scheduled, then each chromosome would be a permutation of the integers from 1 to N. As the GA runs, the selection, mutation, and crossover operations make gradual changes to the ordering of the integers in the permutations on the chromosomes. Consider an unrealistically small example with $N = 10$, and population size = 6. If we initialize the chromosomes with random permutations, they might appear as in figure 4.

Chromosome Initialization

The hsGAo model has several options for chromosome initialization. These options are named *random*, *first*, and *best*. As the name implies, *random* initialization generates a different random permutation on each chromosome in the population. The *first* and *best* initialization options both initialize chromosomes by transforming old schedules into permutations. The old schedules would have been generated by a prior execution of the model, or by another harvest scheduling model. For the *first* initialization option, the permutation is arranged so that stands scheduled in period one in the old schedule are placed at the beginning of the chromosome, stands scheduled in period two are placed next, and so on. For the *best* initialization option, the permutation is arranged so that stands that are scheduled by their optimum (best) period are placed at the beginning of the chromosome, stands that are scheduled one period away from their optimum period are placed next, and so on.

Chrom.	Integer Position on Chromosome									
No.	1	2	3	4	5	6	7	8	9	10
1	7	4	1	9	3	6	5	8	2	10
2	9	2	4	7	1	3	6	8	10	5
3	8	1	2	9	3	10	5	4	6	7
4	6	2	4	5	9	10	8	1	7	3
5	3	1	9	6	8	2	10	5	4	7
6	10	9	4	5	3	7	2	1	8	6

Figure 4.—*Simple example of chromosome format for hsGAo harvest scheduling model.*

Genetic Algorithm Operators

The hsGAo model allows the user to choose among several options for the genetic algorithm operators (selection, crossover, mutation, fitness, and replacement). Selection operator options include *proportional*, *SUS* (stochastic universal sampling), *tournament*, and *probabilistic tournament*. Crossover operator options include *order-based*, *position-based*, and *partially matched*. Mutation operator options include *order-based* and *position-based*. Fitness operator options include *raw*, *normal*, and *ranking*. Replacement operator options include *best*, *random without replacement*, and *random with replacement*. For the replacement operators, each option can be used with or without duplicates allowed. Discussion of how all of these operators function is beyond the scope of this paper. They are all well documented in the genetic algorithm literature (Goldberg 1989, Davis 1991).

The Evaluation Function[3]

The GA operators manipulate the permutations on the chromosomes. Each new chromosome that is created during the GA run is fed to the evaluation function to see how good the chromosome is. The evaluation function uses the permutation of stand numbers represented on the chromosome as a list giving the order by which to place stands into the schedule.

Stands are placed into the schedule by one of four scheduling methods: *first*, *best*, *smart-first*, and *best-probabilistic*. All four scheduling methods place stands into the schedule so that maximum volume restrictions and adjacency constraints are not violated. The four methods differ in how they choose where in the schedule (which regime/period) to place stands. They also differ in how they handle the minimum volume restrictions. The general scheduling algorithm for all four methods is shown in figure 5.

```
S_i ← 0, ∀i
FOR i' = 1 TO N
        i ← extract stand number from position i' on
            chromosome
        S_i ← regime chosen for stand i by the schedul-
            ing method
NEXT i'
```

Figure 5.—*General scheduling algorithm used in the order-based genetic algorithm evaluation function.*

The *first* scheduling method places each stand into the first (lowest numbered) planning horizon period without violating (3) or (4). The *best* scheduling method places each stand into the planning horizon period that gives it its highest (best) NPV available without violating (3) or (4). The *smart-first* scheduling method schedules stands in period one until the minimum volume for the period is met, then moves to the second period, and so on. After the minimum volume restrictions have been met for all periods, the *smart-first* method reverts to the *best* scheduling method for the remaining stands. The *best-probabilistic* scheduling method is similar to the *best* method. It differs in that when choosing the best period, it performs a biased selection from among the legal periods. The bias favors the period with the highest NPV, but provides the chance that some sub-optimum period is selected for the stand.

The choice of which scheduling option is used for a particular run affects the choice of the chromosome initialization option. The *first* initialization method is used with the *first* and *smart-first* scheduling options. The *best* initialization method is used with the *best* and *best-probabilistic* scheduling options. The *random* initialization option can be used with any scheduling method.

A pseudocode description of the evaluation function design for hsGAo is given in figure 6 which spans the next few pages. The pseudocode includes four modules named *evaluate*, *place_stand*, *get_per*, and *set_per_now_scheduling*. Module *evaluate* is the top level module. It is called by the genetic algorithm driver routine, and it calls *place_stand* and *set_per_now_scheduling*. Module *place_stand* calls *get_per*. A fifth module, *is_size_violation*, which is called by *place_stand*, is not given here. *is_size_violation* tests to see if placing the stand into the schedule in the period being tried will cause an opening size violation. Pseudocode for function *is_size_violation* is given in (Mullen 1996, 1997).

[3] *This section is taken almost verbatim from Mullen (1996).*

FUNCTION evaluate (*c*)

// Evaluation function for order-based genetic
// algorithm harvest scheduling model.
local data: Q, *VSUM*, i, i', Z_{vmin}
global data: *sched_opt*, *per_now_filling*, N, P, Z, S, V, D, *VMIN*

$Q \leftarrow 0$; $S_i \leftarrow 0$, $\forall i$; $VSUMj \leftarrow 0, \forall j: j \in [1,P]$
IF *sched_opt* = SMART_FIRST_SCH THEN
    per_now_filling ← 1 // Start filling period 1.
    CALL set_per_now_filling( )
ENDIF
FOR i' = 1 TO N // Place N stands into the schedule.
    $i \leftarrow c[i']$ // get next stand number from chr.
    $S_i \leftarrow$ place_stand(i)
    $Q \leftarrow Q + D_{iSi}$// Sum NPV and Volumes.
    IF $Si \leq P$ THEN $VSUM_{Si} \leftarrow VSUM_{Si} + V_{iSi}$
    // For SMART_FIRST_SCH option, adjust
    // *per_now_filling* if needed.
    IF *sched_opt* == SMART_FIRST_SCH THEN
        CALL set_per_now_filling( )
    ENDIF
ENDFOR
// Deduct minimum volume restriction violation.

$$Z_{vmin} \leftarrow Z\left(\sum_{j=1}^{P} \max(0, VMINj - VSUMj)\right)$$

$Q \leftarrow Q - Z_{vmin}$
RETURN Q
END FUNCTION evaluate

FUNCTION place_stand(*i*)

// Find regime/period in which to schedule stand.
local variables: j, *vol*
global data: P, S, V, ADJ, $VMAX$, $VSUM$
// Get the first period to be tried.
j ← get_per(i, TRUE)
// Loop until scheduling stand i in period j doesn't
// violate restrictions or j is set beyond end of
// planning horizon.
DO WHILE $j < P+1$
    // Test for volume restriction violation
    $vol \leftarrow VSUM_j + V_{ij}$
    IF $vol \leq VMAX_j$ THEN
        IF $|ADJ_i| = 0$ THEN RETURN j
        $S_i \leftarrow j$ // Test for opening size violation
        IF NOT is_size_violation(i) THEN
            RETURN j
        ENDIF
    ENDIF

    $j \leftarrow$ get_per(i, FALSE) // Get next period to try.
ENDDO
RETURN (P+1) // Assign do-nothing regime.
END FUNCTION place_stand

Figure 6.—*A pseudocode description ohe evaluation function design for hsGAo.*

(Figure 6 continued on next page)

(*Figure 6 continued*)

```
FUNCTION get_per(i, init)
// get_per returns a period to try to schedule stand i.
local variables: j
global data: sched_opt, per_now_filling, P, S+, D, σ
DO CASE sched_opt
    CASE FIRST_SCH    // Schedule in first period
        IF init THEN  // that does not cause any
            j ← 1     // violations.
        ELSE
            j ← j + 1
        ENDIF
    CASE BEST_SCH     // Schedule in best period
        IF init THEN  // that does not cause any
            j ← S+_i  // violations. S+_i is opt-
        ELSE          // imum regime for stand i
            IF all regimes already tried THEN
                j ← P + 1
            ELSE
                j ← next best untried regime
            ENDIF
        ENDIF
    CASE SMART_FIRST_SCH
        // Try to schedule in per_now_filling on
        // first try. On rest of tries, use next best
        // untried regime. If VSUM_j has reached
        // MINV_j for all j, then revert to BEST_SCH
        // scheduling method.
        IF init THEN
            IF per_now_filling ≤ P THEN
                // Try to schedule in
                // per_now_filling on first try.
                per ← per_now_filling
            ELSE
                // Use best regime for stand.
                per ← S+_i
            ENDIF
        ELSE
            j ← next best untried regime
        ENDIF
    CASE PROB_SCH
        IF init THEN
            // On first try for a stand, use probabi-
            // listic regime selection. Set initial try
            // to optimum period +/- random move.
            j ← S+_i // optimum regime for stand i
            j ← randomly choose period from

                normal distribution with mean
                of j and standard deviation of σ
            IF j < 1 THEN j ← 1
            IF j > 1 P + 1 THEN j ← P + 1
        ELSE
            // On rest of tries, choose next best
            // untried period.
            IF all regimes already tried THEN
                j ← P + 1
            ELSE
                j ← next best untried regime
            ENDIF
        ENDIF
ENDCASE
RETURN j
END FUNCTION get_per


BEGIN PROGRAM set_per_now_filling( )
// Set per_now_filling to the first period that has
// VSUM_per_now_filling < VMIN_per_now_filling.
global data: P, VSUM, VMIN, per_now_filling
WHILE per_now_filling <= P + 1
    IF VSUM_per_now_filling < VMIN_per_now_filling THEN
        RETURN
    ENDIF
    per_now_filling ← per_now_filling + 1
END WHILE
RETURN
END PROGRAM set_per_now_filling
```

MODEL IMPLEMENTATION AND TEST RESULTS

For his thesis, Mullen developed a C language implementation of the hsGAo model (Mullen 1996). His thesis supplies the source code and user's guides for this model implementation plus two other models. The hsGAo program uses a genetic algorithm library named PGAPack that is publicly available at several sites on the Internet (Levine 1995). The PGAPack library provides the GA driver routines, routines to create and manipulate the population of order-based chromosomes, and the selection, fitness, and replacement operators. It does not include order-based mutation and crossover operators, so routines were developed by Mullen to implement these.

Also for his thesis, Mullen ran timed test runs to compare how well the hsGAo program did finding near-optimum solutions compared to two other models. One of these models, hsGAt, used a traditional GA in which the solution ($\boldsymbol{S}$) was represented directly on the chromosomes. The other model, hsMCIP, used a Monte Carlo integer programming technique based on the models presented by Nelson *et al.* (1988). In the timed test runs, performance of the order-based GA model (hsGAo) averaged 2.20 percent higher than the traditional GA model (hsGAt) and 3.55 percent better than the MCIP model (hsMCIP). The test runs were executed for six different harvest scheduling problem data sets. The data sets ranged from 42 to 849 stands, 10 to 15 planning horizon periods, 0.95 to 4.77 adjacencies per stand, and 2-period to 4-period period exclusion periods. A side question that was investigated in a series of test runs was: "How close to being optimal are the hsGAo program solutions?" Results of test runs without adjacency constraints showed that hsGAo could easily find solutions that were about 99.8 percent of the LP optimum solutions for four of the six data sets, 99.7 percent for one data set, and 99.0 percent for one data set (Mullen 1996).

Mullen's employer, Rayonier, Southeast Forest Resources, has successfully used the hsGAo program to develop operational harvest schedules for 90 percent of its timberland holdings in Florida and Georgia. For the 15 forests that were scheduled, the hsGAo program found spatially constrained harvest schedule solutions that had an average NPV only 1.7 percent less than non-spatially constrained LP optimum solutions.

CONCLUSION

We have reviewed the design of a spatially constrained harvest schedule optimization model that uses a combination of an order-based genetic algorithm and an heuristic scheduling algorithm as the optimization techniques. Results from test runs and operational use show the hsGAo model to be a highly efficient model for optimizing large scale spatially constrained timber harvest scheduling problems.

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SPATIAL FOREST PLANNING ON INDUSTRIAL LAND: A PROBLEM IN COMBINATORIAL OPTIMIZATION

Karl R. Walters[1]

ABSTRACT.—Recently, member companies of the American Forest & Paper Association adopted guidelines for the management of their lands that impose significant challenges to harvest scheduling. In particular, foresters face difficulties not only in scheduling harvest blocks, but even in delineating them. The spatial forest-planning problem (SFPP) involves simultaneous allocation and scheduling of cells to form harvest blocks that meet adjacency, green-up and opening-size constraints. A preliminary investigation of simulated annealing and tabu search was made to test their suitability to the SFPP. Simulated annealing yielded better solutions and shorter execution times for a number of contrived but otherwise representative problems.

INTRODUCTION

Harvest scheduling is a traditional exercise that has been carried out by forest land managers on public and private lands alike. Industrial forest management has generally been distinguished by a much higher rate of intensification than has been the case on public lands. Whereas public land management has characteristically balanced timber and non-commodity forest production, industrial plantation establishment has been dominated by profit maximization and cost reduction through economies of scale. The result is a patchwork of large, uniform even-aged plantations of very high productivity that have been able to meet society's demand for high quality and affordable forest products.

Unfortunately, the same public that demands forest products at low cost has made it clear to the forest industry that it does not favor the large clearcut areas that have been characteristic of southern pine plantations. In response, member companies of the American Forest and Paper Association (AF&PA) have agreed to comply with the Sustainable Forestry Principles and Implementation Guidelines; other companies have adopted their own set of guidelines to promote sustainable forestry. These new principles place renewed emphasis on non-timber resources and require that harvest operations be scheduled according to spatially specific objectives that call for smaller scale harvest operations and diversification of harvests over the landscape. Forest companies are now facing the challenge of scheduling spatially specific timber management activities over time to achieve their traditional objectives and the new environmental goals.

The Nature of the Problem

Champion International is a large forest-products company with land holdings throughout the United States with significant acreage throughout the Southeast and into Texas. Like most other companies in the region, the bulk of these forest lands have been managed as southern pine plantations. These plantations are typically large (several hundred to upwards of several thousand acres) and have been harvested multiple times with rotations ranging from 10 to 30 years, depending on growth rates. Harvest scheduling has typically been done based on maximization of present net worth and land expectation value, and concentrating harvesting operations near one another has been used to minimize harvest costs. The resulting landscape is generally one of overwhelming uniformity, with large tracts of the same species of very similar age.

Champion's new Sustainable Forestry Initiative (SFI) is based on the AF&PA guidelines, but operating guidelines are at least as strict and sometimes more restrictive than those set out by AF&PA. For example, clearcut harvesting is limited to areas less than 240 acres and only where necessary will clearcut areas exceed 120 acres. Clearcut harvest areas are considered *contemporary* if they are established within a fixed number of years of one another. Until better estimates of regeneration response are known, Champion has conservatively set the *green-up period* at 4 or 5 years in most regions. Clearcutting will not be permitted within 300 feet of a contemporary clearcut harvest area unless a water course that requires more restrictive riparian zone management separates the two.

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Although it is quite easy to state that forest management planning as an activity is deciding what activities to implement, in what place and at what time, the actual process of making these determinations is far from easy. In years past, locating a harvest activity had little consequence elsewhere in the forest or in future years, except for the fact that the harvested timber was no longer readily available. In modern planning situations, the location of a harvest activity can have impacts on large areas of the forest by making them unavailable for harvesting, not only in the current planning period, but for future ones as well. A poor choice made in past years can severely limit options in future periods. In the case of Champion and other companies operating in the southeast, past practices are probably the biggest obstacles to overcome under the new operating guidelines. In general, making harvest blocks as large as possible and keeping green-up delays as short as possible is the best way to mitigate adjacency constraints.

Champion is not unique with its SFI and other companies in the southeast have adopted similar operating principles. In fact, the majority of forest companies implementing these new types of operating guidelines face similar difficulties in implementing them. They require some method of determining spatial harvest schedules in a timely manner, and they have to contend with a major shift in harvesting logistics associated with smaller harvest areas dispersed over much wider areas. The purpose of this paper is to discuss some alternative strategies for solving spatially constrained harvest schedules and the kinds of results to expect.

Literature Review

Linear programming has long been the primary method for developing long-term forest management schedules. As the need for spatial feasibility in these schedules became more common, it was only natural that researchers tried to incorporate spatial constraints within their preferred modeling framework. For example, we have seen the development of aggregate emphasis and coordinated allocation choice formulations within FORPLAN, but these formulations assume previously defined activities schedules and layouts (Connelly 1988). For a single watershed, developing one or two spatially feasible activity schedules is possible, but for an entire forest this task is not feasible. Furthermore, there is no guarantee that such schedules are even close to optimal given the exceedingly large number of alternative layouts that are possible.

Meneghin *et al.* (1988) demonstrated methods of efficiently coding adjacency constraints within a mixed-integer programming formulation. The rationale for this approach is to limit the number of constraints in the integer formulation to fit within the capabilities of commercial IP codes: if a given problem can be correctly represented by fewer constraints, then a correspondingly larger problem should be solvable. This paper spawned many other papers seeking even more efficient ways of structuring adjacency constraints (Torres-Rojo and Brodie 1990, Jones *et al.* 1991, Yoshimoto and Brodie 1994). Murray and Church (1995a) compared many of these different approaches and found that structures that yielded the fewest constraints increased computational effort rather than decreasing it. Snyder and ReVelle (1996) used derivations of the pairwise methods of Meneghin *et al.* (1988) to solve spatial harvest schedules using simplex with limited branching and bounding. All of these approaches assume that harvest blocks are previously delineated and that the adjacency restrictions prevent adjacent blocks from being harvested simultaneously.

O'Hara *et al.* (1989), Clements *et al.* (1990) and Nelson and Brodie (1990) all developed mixed-integer harvesting formulations with pairwise harvest adjacency constraints and none used linear programming with branch and bound to find solutions. O'Hara *et al.* (1989) used a biased sampling search technique and the latter two used Monte Carlo Integer Programming (MCIP). Although it required previously defined harvest blocks, the BLOCK heuristic presented by Clements *et al.* (1990) differed from the other heuristic approaches in that it only prevented adjacent blocks from being harvested simultaneously when the opening created was too large. This type of formulation has not been demonstrated in LP-based systems.

Lockwood and Moore (1993) gave an example application of spatial harvest scheduling using simulated annealing (SA) where each stand in the forest could be considered for a single treatment over the planning horizon but a large number of stands were involved. To make harvesting economically feasible, the algorithm is forced to aggregate adjacent stands into harvest blocks, assigning penalties to instances where blocks are too small or too large. Similar types of penalties are applied to prevent adjacent stands from being harvested within the green-up period. Murray and Church (1995b) used three different heuristic solution methods (interchange, SA, and tabu search (TS)) to solve spatially constrained harvest schedules that also included road construction decisions and they reported near optimal results for short planning horizons.

Remsoft Inc. (1996) has developed a spatial forest planning system based on a two-tier approach linking strategic and tactical planning. The system uses linear programming to develop a strategic harvest schedule that reflects long term goals such as harvest flows, silvicultural costs, forest structure requirements, and so forth. The strategic harvest schedule is then used to guide a

blocking and scheduling algorithm (Stanley) that uses local improvement and random restart heuristics to generate spatially feasible harvest schedules for a shorter tactical planning horizon. The system has been applied to numerous public land and industrial forest planning situations with good success.

In relation to the spatial forest planning problem (SFPP) faced by Champion International and other industrial forest land owners, the methodologies outlined have major drawbacks. Foremost is the assumption that one can delineate good harvest block allocations *a priori*. Remsoft Inc. (1996) compared spatial harvest schedules prepared by Crown land licensees in New Brunswick with schedules prepared using the *Crystal* (Jamnick and Walters 1993) and *Block* (Clements *et al.* 1990) algorithms to generate harvest blocks and schedule them under adjacency constraints. Their findings suggested that manually delineated blocks resulted in sustainable harvest levels that were significantly lower than the heuristically obtained schedules, even though both processes used identical forest stratification and yield estimates. This would suggest that at least some of the *losses* associated with spatial constraints are in fact due to poor block configuration.

Although the work on incorporating adjacency constraints within a mixed integer programming formulation have yielded interesting results from a theoretical standpoint, the ability to solve large-scale harvest scheduling with adjacency constraints is still elusive. Unlike the simple adjacency concept used in most papers, the SFI guidelines would require recognition of proximal polygons that are within 300 feet as adjacent polygons, significantly increasing the number of adjacency relationships to contend with.

One of the drawbacks to the Stanley algorithm is its dependence on the strategic harvest schedule to assign harvest-timing choices to forest types. In the absence of adjacency information, an LP-based harvest schedule can easily assign more acres to a harvest prescription in a given period than would be allowed when spatial constraints are applied. For example, suppose the LP assigns all of a forest class to be harvested in a single period. If the class is made up of a single plantation that exceeds the maximum opening size, then it cannot all be harvested in one period. Alternatively, the class may be composed of many stands too small to be harvested on their own economically. Unless all of these stands have eligible neighbors they can be combined with, there is no way to liquidate the entire class according to the LP schedule. Obviously, deviations from the LP schedule are necessary to meet the spatial requirements and the solution may be driven further from true optimality as the scheduling algorithm tries to mitigate the penalties. That said, the Remsoft algorithm generally performs very well.

The SA algorithm presented by Lockwood and Moore (1993) worked with individual stands and to apply this algorithm to the spatial forest-planning problem as outlined, stands need to be subdivided into smaller pieces. Although the authors suggested that subdividing stands might be helpful to mitigate block size problems, they did not pursue it. Increasing the number of allocation units should not pose untoward difficulties, but the algorithm would need to be modified to recognize the difference between adjacent and proximal polygons: only adjacent stands are used to develop harvest blocks, but proximity is important for determining if adjacency restrictions apply.

Combinatorial Nature of the Problem

The SFPP simultaneously allocates polygons to harvest blocks and schedules those blocks for harvest under adjacency constraints. Even if we ignore the scheduling aspect for the moment and consider only a single harvest activity, the problem still grows exponentially in the number of periods to plan for. For example, suppose we wish to know how much of a given plantation can be harvested in a single period. If the plantation is composed of 10 cells, there are 2^{10} or 1,024 potential arrangements of those 10 cells and if the plantation is composed of 100 cells, there are 1.267×10^{30} combinations. Now, consider that there may be tens of thousands of cells and up to 20 harvest periods and the number of alternatives quickly becomes astronomically large. Since enumeration and deterministic algorithms like branch and bound are not feasible for problems of this size, the alternative is to consider heuristics.

Heuristic approaches are based on the idea of making incremental improvements by changing elements of a solution iteratively. Although the SFPP offers a very large number of alternatives, many of them represent infeasible solutions and the feasible region is not a continuous space. If one considers one-at-a-time changes to the solution space, each change represents a neighbor solution and the size of this neighborhood is a function of the number of possible changes. For example, if the planning problem has a planning horizon of 4 periods (plus a no-harvest option), then changing the harvest period of a single cell results in a neighborhood of size 4. If the proposed change involves swapping the harvest period of two cells in the forest, then the neighborhood size is much larger: $n(n-1)/2$ where n is the number of cells in the forest. Computation time for estimating effects of a proposed change to a solution are generally a function of neighborhood size and the larger the neighborhood, the more computation that will be required. If it is computationally expensive to evaluate the objective function, the choice of neighborhood is critical to maintain reasonable run-times.

While neighborhood size is an important consideration in implementing a heuristic approach, the terrain of the neighborhood is also a consideration. Ideally, the neighborhood chosen is neither flat (objective function remains the same over many changes) nor overly steep (objective function changes by large values with each modification to the solution). Because the spatial requirements make many of the alternative solutions infeasible, there are two recourses for finding solutions: either maintain feasibility at all times with significant computational effort or, as is most common, forego feasibility but penalize solutions for violating spatial constraints. Although the use of penalties reduces computational burden, neighborhoods in the SFP problem tend to have a spiky neighborhood because of the spatial requirement penalties. Depending on the heuristic being used, these spikes may make it difficult to converge to a good solution.

METHODS

For this paper, I considered two different heuristic approaches: simulated annealing (SA) and tabu search (TS). Both are really extensions of a local improvement algorithm where changes are proposed and accepted only if they improve the objective function value. The algorithm continues to run until no further improvement is possible. While local improvement algorithms can become trapped at a local optimum, the SA and TS algorithms avoid becoming trapped by allowing changes that lead away from the local optimum. Each of these approaches has yielded good results for different combinatorial optimization problems, but neither is universally superior. The purpose of this paper is to determine the relative advantages and disadvantages of these algorithmic approaches with respect to the SFP.

Simulated Annealing

Numerous references are available that discuss the structure of SA algorithms (Kirkpatrick *et al.* 1983, Johnson *et al.* 1989) so I will not go into great detail. Basically, a SA algorithm begins with an initial solution S, and a definition of neighborhood that allows perturbation of a solution. If a perturbation results in an improved objective function value, the move is accepted. If the move does not improve the objective function value (an uphill move), it may still be accepted and the probability of acceptance depends on the magnitude of the change and a temperature parameter (T).

Initially, the value of T is set to a high value such that the probability of accepting an uphill move is similarly high, but as the algorithm progresses, the temperature parameter T is gradually lowered such that uphill moves are accepted less and less frequently (table 1). Johnson *et al.* (1989) suggest an initial temperature where about 40 percent of moves are accepted. Temperature reductions are performed after a fixed number of moves and the algorithm terminates when the number of moves accepted falls below a threshold value and no improvements to the objective function have after a fixed number of moves. The SA algorithm used in this study did not incorporate any special modifications and conformed to the suggested structure of Johnson *et al.* (1989).

Tabu Search

Rather than selecting one neighboring solution and deciding to implement the move or not as is done in SA, a TS algorithm evaluates all of the neighboring solutions and implements the move that improves the objective function value most. If all of the moves are uphill moves then the TS implements the move that reduces the objective function value by the smallest amount. Although these occasional uphill moves provide a means for escaping local optima, a mechanism is required to prevent the algorithm from immediately returning to the previous value when that neighborhood is revisited next time.

The key feature of TS is the use of short-term memory to guide searching the solution space (Glover 1990). To better understand this metaphor, consider branch and bound to be a long-term memory algorithm: once a node in a branch and bound tree has been fathomed, the algorithm *remembers* this and never returns to it. On the other hand, SA is a memory-less algorithm because its traversal of the solution space is completely random, and it may make the same move many times over the course of an annealing run. In tabu search, once a move has been accepted, that move is made taboo for a period of time to force the algorithm to explore other parts of the solution space. The period of time a move is taboo is called the tabu tenure (table 2).

Some other features of TS are the concepts of aspiration criteria and diversification. Basically, the idea behind aspiration criteria is that occasional tabu moves may be allowed if they advance to a more desirable solution. Commonly, aspiration criteria are defined as moves that yield a better solution than any found thus far, and when the TS encounters such a move, the aspiration criteria override the tabu status and allow the move to proceed anyway. Diversification is used when improvements in objective function value become too infrequent and a change is made simply to cause the algorithm to search another part of the solution space in hopes of finding better solutions. Diversification may include complete restarts with a new random solution, or some larger scale perturbation of the current or candidate solution. The algorithm terminates when a fixed number of diversification moves are made without improving the objective function value. The TS algorithm used in this study basically follows the suggestions of Glover (1990);

diversification was accomplished by randomly changing the harvest periods of cells within the candidate solution.

RESULTS

To make the comparisons between SA and TS fair, both algorithms employed the same evaluation routines. The user specifies the minimum and maximum block size as well as the length of green-up period required between adjacent harvest blocks. To prevent violations of the spatial constraints, penalties are applied at the rate of 2000 units per block-adjacency violation and 200 units per size violation. If even flow constraints are applied, the objective function is calculated as: *Z= MIN(periodic harvest)+0.2*(total harvest)-0.1*(range in harvest levels)-adjacency_penalty-size_penalty.* Without even flow constraints, the objective function is simply *Z=(total harvest)-adjacency_penalty-size_penalty.*

To test how well these algorithms perform, I set up a number of small test problems to measure quality of solution and execution time. Each algorithm was run 10 times for each problem instance with the best and average performance noted.

Plantation Liquidation Problem

The plantation liquidation problem considers the problem of a plantation that was established with the idea of liquidating it in one harvest. Given the new operating guidelines in place, how much of the plantation can be liquidated in a single pass and how long does it take to liquidate the entire plantation with economically viable harvest blocks? To model the latter, I assumed a base value of 100 for cells cut in the first year, no growth in future period and a 4 percent discount rate. Although plantations in the south will most certainly continue to grow beyond their economic rotation age, higher discount rates will depreciate their value more quickly. The results in table 3 include 4 different sized problems where the single pass liquidation was used and a single SA was able to find the optimal solution in every instance of the 7x7 and 5x10 problem sets and came very close to the optimal each time in the 10x10 and 5x20 problem sets. The TS algorithm fared less well but was still able to find the optimal solution at least once in 10 runs for each of the smaller problem sets. On the larger problems, the TS algorithm performed significantly poorer than the SA algorithm. For a single run on a 25x25 problem set, SA produced what appears to be a rational means of solving the problem: make blocks as large as possible separating them by a minimum width buffer; additional cells are left unharvested to avoid exceeding the maximum opening size.

The solutions to the second liquidation problem (table 4) were more varied, but overall the algorithms tried to make period 1 blocks as large as possible while creating harvest blocks to be harvested in subsequent periods in the buffer areas. If these blocks are unacceptable, it may be necessary to place constraints on block shape to discourage *tentacles*.

Table 1.—*Parameter settings for simulated annealing algorithm*

Parameter	Value	Purpose
L	20 * polygons in forest	Determines the number of perturbations to attempt before reducing the temperature parameter
Tfactor	0.95	Multiply T by tfactor to reduce T after L moves attempted
Minpercent	0.02	Threshold for determining stopping criteria; if no improvement in objective function value after 10 temperature reductions, STOP
Initprob	0.40	The initial temperature is varied up and down in an abortive annealing run to determine a temperature at which about 40 percent of the moves are accepted.

Table 2.—*Parameter settings for tabu search algorithm*

Parameter	Value	Purpose
Tabu tenure	k periods where k=#polygons in forest	Determines the length of time (iterations) a move is not allowed
Diversification count	20	Algorithm terminates after 20 diversification moves

Table 3.—*Results of applying SA and TS algorithms to the single pass plantation liquidation problem*

Problem	Simulated Annealing results			Tabu Search results			Optimal solution value
	Best solution	Average	Average # iterations	Best solution	Average	Average # iterations	
7x7	21000	21000	37600	21000	19200	21400	21000
5x10	22500	22500	37800	22500	21050	22300	22500
10x10	40500	40100	222800	37000	35200	51300	41000
5x20	42500	41800	78200	37500	35400	31100	unknown

Table 4.—*Results of applying SA and TS algorithms to the problem of complete plantation liquidation*

Simulated Annealing results				Tabu Search results			
Best solution	Average	Average # iterations	Max./Min periods req.	Best solution	Average	Average # iterations	Max/Min periods req.
48475	47725	179800	12/5	42708	35683	222600	13/10

Table 5.—*Results of applying SA and TS algorithms to different 100 cell forests with even-flow constraints*

	Simulated Annealing results			Tabu Search results		
	Best solution	Average	Average # iterations	Best solution	Average	Average # iterations
4 types in 4 stands	31332	28655	154400	9020	6922	321800
4 types, random	67060	58232	167600	8922	7896	361500
1 type	16538	15673	132400	8820	7960	244000

Harvest Scheduling Problem

Although the liquidation problem is an interesting stand-level question, it has limited applicability in a forest-wide context. A more relevant question is to what happens when even flow constraints must also be satisfied. Unlike linear programming solutions that allow infinite divisibility of decision variables, the SFPP forces outputs to be produced in discrete quantities. How well the algorithm is able to balance flows is a function of the size of the problem formulation and the relative effect of a single cell on forest-wide output levels. With a small forest, it may be quite difficult to achieve even the semblance of even-flow whereas on large forests, even-flow can be easily attained (table 5).

Again, SA did markedly better than TS in both execution time and quality of solution. In fact, TS yielded exceedingly poor results for the 4-stand and random-stand problems. However, with the uniform forest type, the TS algorithm performed almost as well as the SA. Harvest flows produced using SA were very good for the uniform forest (+/- 4%) and less acceptable for the multi stand cases (+72/-42% for random, +30/-19% for 4-stand).

DISCUSSION

Neither algorithm was implemented for use outside of this study and overall performance of the programs could be improved dramatically. Both algorithms used the same evaluation procedures and improving the efficiency of

these procedures would speed up both programs. Since the complete evaluation routine is much more computationally intensive, any improvements in its efficiency would be of greater benefit to the TS algorithm that calls that procedure multiple times during execution. Nevertheless, the simulated annealing algorithm appeared to be a better performer overall, not only in terms of execution time but also in the quality of solutions.

I suspect the poorer performance of the tabu search is due to the spiky neighborhood referred to earlier. Because the TS algorithm always implements the best move available, even if it is uphill, it may take several hundred iterations before the algorithm can recover. Whereas the SA accepts uphill moves with very low probability when it has very nearly converged, the TS will continue to make uphill moves regularly. More fine-tuning of the tabu tenure and diversification rates can probably improve the performance for a specific problem instance, but the SA seems to be more robust in this regard.

Both algorithms did better on the simpler plantation liquidation problems than on the harvest scheduling problems with flow constraints. Fine-tuning of parameters could yield better results but the SA was more robust overall, particularly when a mix of forest types was encountered. Why the TS performed so poorly on these two problem sets but not on the others is unknown.

Execution times remain a concern. The problems used in this study are trivial and yet required significant computational effort to solve. A realistic sized problem would have as many as 100 to 1,000 times as many cells as the largest problem used in this study. Faster processors and optimized coding can dramatically improve performance but it may be that long processing times are unavoidable. Given the complexity of the SFPP, significant computational effort is surely worthwhile, but the question is whether the quality of solutions using SA or TS are significantly better than alternative methods such as the Stanley algorithm which yield good results in a short time.

For now, SA seems to be a logical choice for further development of a model formulation for the SFPP. It seems to adapt fairly well to different objective functions and constraints and remains fairly straightforward to implement. Data structures to represent the SFPP need to be carefully developed to maximize the efficiency of the evaluation function, since it is by far the most computationally intensive part of the algorithm and is called many times. For a large-scale instance of the SFPP, efficiency will be an overriding concern to keep execution times reasonably short.

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AN OPTIMAL APPROACH AND ALGORITHMS FOR LIMITING FOREST OPENING SIZE IN SPATIALLY CONSTRAINED TIMBER HARVEST SCHEDULING MODELS

David S. Mullen[1]

ABSTRACT.—It is assumed that the reason for including spatial constraints in harvest scheduling models is to place an upper limit on the size of forest openings that occur due to clearcutting. An optimal approach to enforcing this limitation is to allow adjacent stands to be cut in any planning horizon period, as long as, at any point in time, the combined area of any group of adjacent stands that forms an opening, does not exceed the maximum allowed opening size. Two algorithms are presented that can be used in harvest scheduling models to implement this approach.

INTRODUCTION

Increasingly, forest managers are being required to include spatial restrictions in their operational harvest schedules. These restrictions are imposed due to concern for maintaining and enhancing wildlife habitat, biodiversity, watershed integrity, and esthetic appeal (Hokans 1983, Rosie 1990, Lockwood and Moore 1993, Weintraub *et al.* 1995).

This paper describes an optimal approach to including spatial constraints in harvest scheduling optimization models. In addition, it provides an informal proof that the approach is optimal and gives algorithms that can be used with heuristic and random search harvest scheduling models. The approach and algorithms were previously described and used in the author's master's thesis (Mullen 1996).

BACKGROUND

Different approaches have been proposed and used to include spatial constraints in harvest schedule optimization models. The two general approaches that have been used most often are the adjacency constraint approach and the opening size restriction approach. These are discussed in the following sub-sections.

Adjacency Constraint Approach (Non-Grouping Approach)

With the adjacency constraint approach, spatial restrictions are formulated so that adjacent stands are not allowed to be harvested within a specified green-up time period of each other. The green-up time period is referred to as the exclusion period, and represents the number of planning horizon periods needed for a harvested stand to be regenerated and grow to some arbitrary age or tree height. Because this approach does not allow stands to be grouped together for harvest in the same period, we will also call this the "non-grouping approach." Following are a few examples of the many models that have been developed that use adjacency constraints.

Nelson *et al.* (1988) implemented the non-grouping approach in their Monte Carlo integer programming based model. Each time their model schedules a stand, it sets adjacent stands ineligible for harvest in the same period. This implementation only provides for a one-period green-up. Examples of other heuristic and random search based models that use adjacency constraints include the SCRAM model of O'Hara *et al.* (1989); the ROHO-PATH model of Yoshimoto *et al.* (1994a), and the ECOPLAN system of Misund *et al.* (1995). Some of these models allow for multiperiod green-up exclusion. Much work has been done to develop efficient ways to represent adjacency constraints in mathematical programming based models. The work presented by Yoshimoto and Brodie (1994b) and by Torres-Rojo and Brodie (1990) are examples of just two of the many papers that have used mathematical programming models with adjacency constraints.

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Opening Size Restriction Approach (Grouping Approach)

It is often desirable to allow groups of adjacent stands to be harvested together if their combined area does not exceed a maximum allowed opening size. With this approach, the goal is not to prevent adjacent individual stands from being harvested together, but to prevent adjacent groups of stands from being harvested together in patterns that create forest openings above the maximum size limit.

Mathematical programming based models are not suitable for allowing stand grouping. This is because the number of possible combinations of allowable stand groupings becomes astronomical for large scale scheduling problems and the combinations must be explicitly specified in the problem constraints for each possible combination. For this reason, when we want to allow groups of stands to be harvested together, we are forced to abandon mathematical programming models and turn to heuristic and random search models.

Examples of harvest scheduling models that use opening size restrictions include Dallain's BLOCK model (Dallain 1989), Baskent's GISFORMAN model (Baskent 1990), Lockwood and Moore's (1993) simulated annealing based model, and Jamnick and Walters (1991) CRYSTAL model. Each of these models uses some sort of grouping algorithm that discourages or prevents opening size restriction violations. Lockwood and Moore's model does not strictly enforce the opening size restrictions, but applies a penalty function to violations. The penalty is proportional to the extent of the violations. This makes the model favor solutions with fewer and less severe violations. In the other models, the grouping algorithms strictly enforce opening size restrictions. All of these models use grouping algorithms that group stands within the same period only. We will refer to this as the "within-period grouping approach."

THE ACROSS-PERIOD GROUPING APPROACH

As part of the author's master's thesis, a more flexible grouping approach and implementation algorithms were developed and used in three spatially constrained harvest scheduling models (Mullen 1996). In the approach developed, groups of adjacent stands are allowed to include stands harvested in different periods within a green-up time period of each other. Because grouping is done across periods, we will refer to the approach as the "across-period grouping approach." The definition of the across-period grouping approach mirrors the basic goal of all spatial restriction approaches, and can be stated as follows:

> The Across-Period Grouping Approach: A harvest schedule does not violate spatial restrictions if, during each period of the schedule, the combined area of each group of adjacent stands that forms a contiguous opening does not exceed the maximum allowable opening size. Stands in an opening group do not necessarily have to be scheduled in the same period.

This approach does not prohibit adjacent stands from being harvested within a green-up time period of each other as is the case with the non-grouping approach. Nor does it force groups of adjacent stands harvested together as a group to all be harvested in the same planning horizon period as is the case with the within-period grouping approach. The only restriction imposed is that openings over a maximum allowable size never occur.

As an example to show how the across-period grouping approach is less restrictive than the other two approaches, consider a "forest" of three 40-acre stands that are all adjacent to each other. Let the maximum opening size be 100 acres, let the planning horizon consist of three 2-year periods, and let the green-up period be 4 years (two periods). Let the management regimes be 1-harvest in period 1, 2-harvest in period 2, 3-harvest in period 3, and 4-do nothing (harvest beyond the end of the planning horizon). Let $\boldsymbol{S} = <S_1, S_2, S_3>$, $S_i \in \{1,2,3,4\}$ denote a schedule. Without any spatial constraints, there are $4^3 = 64$ possible schedules: <1,1,1>, <1,1,2>, . . . , <4,4,4>. If we applied non-grouping adjacency constraints approach, there would be only 16 allowable schedules: <1,3,4>, <1,4,3>, <1,4,4>, <2,4,4>, <3,1,4>, <3,4,1>, <3,4,4>, <4,1,3>, <4,1,4>, <4,2,4>, <4,3,1>, <4,3,4>, <4,4,1>, <4,4,1>, <4,4,1>, <4,4,4>. Note that spatial constraints are not considered for regime 4. If we apply the within-period grouping approach, schedules with two stands cut in the same period and the other stand cut at least two periods away or by the do-nothing regime could be added to the set of schedules from the non-grouping approach. This would give an additional 14 schedules: <1,1,3>, <1,1,4>, <1,3,1>, <1,3,3>, <1,4,1>, <2,2,4>, <2,4,2>, <3,1,3>, <3,3,1>, <3,3,4>, <3,4,3>, <4,1,1>, <4,2,2>, <4,3,3>. If we apply the across-period grouping approach, all schedules except those having all three stands cut within two periods are legal. This would add 19 schedules to the 30 that are legal for the within-period grouping approach: <1,2,3>, <1,2,4>, <1,3,2>, <1,4,2>, <2,1,3>, <2,1,4>, <2,3,1>, <2,3,4>, <2,4,1>, <2,4,3>, <3,1,1>, <3,1,2>, <3,2,1>, <3,2,4>, <3,4,2>, <4,1,2>, <4,2,1>, <4,2,3>, <4,3,2>. The non-grouping approach gives us 16 legal schedules. The within-period grouping approach gives us 30 legal schedules, and the across-period grouping approach gives us 49 legal schedules.

PROOF OF OPTIMALITY OF THE ACROSS-PERIOD GROUPING APPROACH

Following is an informal proof that the across-period grouping approach is optimal compared to the non-grouping approach and the within-period grouping approach.

Let the planning horizon be composed of a consecutive sequence of P L-year periods, numbered 1, 2, . . ., P. Let there be $M = P + 1$ management regimes. Regimes 1 through P each have only one harvest and it occurs in the period matching the regime number. Regime M is the "do-nothing" regime which does not have a harvest in the planning horizon and is not subject to spatial restriction. Let E be the exclusion period or (green-up period) specified as a number of planning horizon periods. For example, if the $L = 4$ and the green-up time is 10 years, then E = CEILING(10/4) = 3. Let O be the maximum allowed opening size. Let ADJ_i be the adjacency list for stand i. Let A_i be the land area of stand i. To prevent opening size violations, stands must be defined such that for every stand, $A_i \leq O$.

Let the symbol α designate the non-grouping approach. With this approach, no neighbor of any stand harvested in period j may be harvested during the interval of planning horizon periods [j - E + 1, j + E - 1]. For example, if stand 1 is scheduled in period 5, the exclusion period is 3 periods, and stand 2 is adjacent to stand 1, then stand 2 could not be harvested in the interval of periods from period 5 - 3 + 1 = 3 to period 5 + 3 - 1 = 7.

Let β be the within-period grouping approach. This is the opening size restriction approach that allows stands to be grouped together for harvest within a given period. With this approach, stands may be grouped for harvest in the same period as long as total area of the group does not exceed the maximum allowed opening size. In addition, no neighbor of a stand or group of stands harvested in period j may be harvested during the interval of planning horizon periods [j - E + 1, j + E - 1]. For a given harvest scheduling problem, let S*β be the set of all schedules that meet the within-period grouping approach spatial restrictions.

Let χ designate the across-period grouping approach. With this approach, the only restriction imposed is that openings over a maximum allowable size never occur during the planning horizon.

For a given harvest scheduling problem, let S^*_α, S^*_β, and S^*_χ be the sets of all possible legal schedules that meet the α, β, and χ spatial restrictions, respectively. To prove that χ is optimal, we need to show that S^*_χ contains S^*_α and S^*_β. Said another way, we need to show that $S^*_\alpha \subseteq S^*_\chi$ and $S^*_\beta \subseteq S^*_\chi$. We can do this by first showing $S^*_\alpha \subseteq S^*_\beta$, and then showing $S^*_\beta \subseteq S^*_\chi$. If we can do that, it will follow that $S^*_\alpha \subseteq S^*_\chi$. The only difference between α and β is that β allows legal-sized groups of two or more adjacent stands to be cut in the same period, whereas α does not. So, S^*_β would contain all schedules in S^*_α plus those schedules where legal sized groups of adjacent stands are scheduled in the same period. Therefore $S^*_\alpha \subseteq S^*_\beta$. The only difference between β and χ is that χ allows legal-sized groups of stands to be scheduled in different periods within an exclusion period of each other whereas β requires that groups be harvested in the same period. So, S^*_χ would contain all schedules in S^*_β plus those schedules where legal-sized groups of adjacent stands are scheduled in different periods within a green-up period. Therefore, $S^*_\beta \subseteq S^*_\chi$. Because $S^*_\alpha \subseteq S^*_\beta$ and $S^*_b \subseteq S^*_\chi$, it follows that $S^*_\alpha \subseteq S^*_\chi$. Since S^*_χ contains S^*_α and S^*_β, then χ is optimal.

ALGORITHMS

This section presents two algorithms that can be used to implement the across-period grouping approach. The algorithms are suitable for use in random search harvest scheduling models, but not to mathematical programming models.

Figure 1 gives the first algorithm. This algorithm, named *is_size_violation*, is intended for use in models that strictly enforce spatial restrictions as hard constraints. It would be called once for each stand as it is added to the schedule to test to see if adding the stand at the period being tested would cause an opening size violation. I returns TRUE if an opening size violation occurs or FALSE if no violation occurs. Figure 2 gives the second algorithm. This algorithm, named *sum_size_violation*, is for use in models that loosely enforce spatial restrictions as soft constraints using a penalty function for opening size violations. It would be called once after the scheduling model has finished building a schedule to determine the sum of the size violation penalty function values. Both algorithms use a common subprogram named *group_adj* that performs a graph traversal to find a group of adjacent stands scheduled within a window of periods that spans a green-up period. The *group_adj* subprogram is given in figure 3. For each stand being tested, *group_adj* is called E times. Each call determines whether the stand being tested participates in an opening with adjacent stands within a window of E planning horizon periods. If so, the subprogram returns the set of stand numbers for the group. Figure 4 provides definitions of the variables, arrays, and sets used in the pseudocode listings of figures 1, 2, and 3.

```
BOOLEAN FUNCTION is_size_violation(i, E, O, P, S, A, ADJ, R)
// Stand i is being added to the schedule. S_i has been set to a regime number in the range [1,P+1].
// All stands, i', that have not yet been added to the schedule have S_i' = 0. To test to see if adding stand i
// to the schedule as regime S_i will cause an opening size constraint violation, execute function
// is_size_violation(..). The return value is TRUE if a violation occurs or FALSE if no violation occurs.
DEFINE LOCAL VARIABLES: i', w, j_beg, j_end, sum, G
IF  Si > P ∨ |ADJi| + 0 THEN                    // If S_i is the do-nothing
        RETURN FALSE                            // regime or stand has no
END IF                                          // neighbors, return FALSE.
FOR w = 1 TO E                                  // We have E windows to test.
        j_beg ← S_i - E + w                     // Define exclusion window.
        j_end ← j_beg + E - 1
        G ← {i}                                 // Initialize group with stand i.
        group_adj(i, j_beg, j_end, P, G, ADJ, S, R)   // Add adjacent stands cut
                                                // within exclusion window.
        IF |G| > 1 THEN                         // Don't test if only 1 stand.
                sum ← Σ_{i'∈G} Ai'              // Sum area of stands in group.
                IF sum > O THEN                 // Have violation if sum of
                        RETURN TRUE             // area for any window > O.
                END IF
        END IF
ENDFOR
RETURN FALSE                                    // Didn't find any violations.
END FUNCTION is_size_violation
```

Figure 1.—*Algorithm to use while a schedule is being built to test each stand as it is added to the schedule to see if adding it will cause an opening size violation.*

```
NUMERIC FUNCTION sum_size_violation(N, E, O, P, Z_a, S, A, ADJ, R)
// Summarize the penalties for adjacency constraint violations for schedule S.
DEFINE LOCAL VARIABLES: local variables: T, G, G' , Z_adj, i, i', j_beg, j_end, size, size_max, w
T ← Ø   ; Z_adj ← 0
FOR i = 1 TO N
        // Stand i doesn't need to be tested if it is scheduled beyond the end of the
        // planning horizon, or if it has no neighbors, or if it is already in T.
        IF (Si > P ∨|ADJi| = 0 ∨ i ∈ ∪ G) THEN NEXT i
                                  G∈T
        size_max ← 0
        FOR w = 1 TO E                                  // Have E windows to test.
                j_beg ← S_i - E + w                     // Define exclusion window.
                j_end ← j_beg + E - 1
                G ← {i}                                 // Initialize group with stand i.
                group_adj(i, j_beg, j_end, P, G, ADJ, S, R)   // Add adjacent stands cut
                                                        // within exclusion window.
                IF |G| THEN                             // Don't care if only 1 stand.
                        size ← Σ Ai'                    // Sum area in group.
                               i'∈G
                        IF  size > O ∧ size > size_max THEN
                                G' ← G                  // Save opening group and size if the acre sum is
                                size_max ← size         // greater than that for any previous window's
                        END IF                          // violation.
                END IF
        END FOR
        // If stand i is part of a multistand group larger than the maximum opening size, add a
        // penalty based on the total grouped area of the group from the time window with the highest
        // group area. Note that if stand i was not grouped, then size_max will still be 0, in which case
        // we don't need to do anything.
        IF size_max > O THEN
                Z_adj ← Z_adj + Z_a•(size_max - O)
                T ← T   {G'}                            // Note: T is a set of sets.
        END IF
END FOR
RETURN Z_adj
END FUNCTION sum_size_violation
```

Figure 2.—*Algorithm to use after a schedule has been built to summarize opening size constraint violations.*

```
PROGRAM group_adj(i, j_beg, j_end, P, G, ADJ, S, R)
// group_adj() constructs a set of stands adjacent to stand i that are harvested within the exclusion window
// [j_beg, j_end]. This is a recursive function. The first level call adds neighbors of the initial seed stand. The next
// level call adds neighbors of the stands added in the first level call. Etc. The recursion performs a depth first
// search of the adjacency graph. Upon initial call to group_adj, G contains only the seed stand. Parameter i must
// be passed by value. All others may be passed by address.
DEFINE LOCAL VARIABLE: i' // unit number of a stand adjacent to stand i.
FOREACH i' ϵ ADJ_i
        IF i' ∉ G THEN
                // The tests against S_i' are to group based on new schedule. The tests
                // against R_i' are to group based on recent harvesting activity.
            IF (S_i' > 0 ∧ S_i' ≤ P ∧ S_i' ≥ j_beg ∧ S_i' (j_end) ∨ (R_i' ≥ j_beg ∧ R_i' ≤ j_end) THEN
                // Stand i' is part of group. Add it to G and recursively call group_adj.
                G ← G ∪ {i'}
                group_adj(i', j_beg, j_end, P, G, ADJ, S, R);        // Recurse.
            END IF
        END IF
END FOREACH
RETURN
END PROGRAM group_adj
```

Figure 3.—*Algorithm for subprogram* group_adj *which is called by algorithms in figures 1 and 2.*

i, i'	=	stand numbers.
w	=	exclusion window index.
j_{beg}	=	beginning period in exclusion window.
j_{end}	=	ending period in exclusion window.
N	=	number of stands in the forest.
E	=	exclusion period in number of planning horizon periods.
O	=	maximum allowed opening size area.
P	=	number of periods in the planning horizon.
$size$	=	sum of acres in a opening group (G).
$size_{max}$	=	maximum size found for opening groups seeded at one stand.
Z_a	=	value penalty per unit of area for adjacency constraint violations.
Z_{adj}	=	sum of value penalties for a group.
S	=	array designating schedule. If $S_{i'} = 0$, stand has not been added to the schedule. If $S_{i'} \epsilon [1,P]$, stand is scheduled in period $S_{i'}$. If $S_{i'} = P+1$, stand is scheduled beyond end of planning horizon.
A	=	array of stand areas — A_i is area of stand i.
ADJ	=	array of adjacency sets — ADJ_i is sets of stand numbers of stands adjacent to stand i. For example, $ADJ_4 = \{7, 9, 10\}$ would indicate stand 4 is adjacent to stands 7, 9, and 10.
R	=	array of recent cut designations. If $R_i < 1$, then it represents the implied recent cut period for stand i. If $R_i \geq (E + P + 1)$, then it means stand i was not recently cut.
G	=	variable for constructing an opening group.
G'	=	variable used to hold largest opening group found.
T	=	variable used for constructing the set T of all non-overlapping opening groups while evaluating adjacency violations.
sum	=	sum of area of stands in a group G.

Figure 4.—*Descriptions of variables, arrays, and sets used in algorithms shown in figures 1, 2, and 3.*

CONCLUSION

I have presented an optimal approach for including spatial restrictions in harvest scheduling optimization models. Also presented were an informal proof that the approach is optimal and algorithms for implementing the approach. The algorithms are suitable for use in heuristic and random search harvest scheduling models that either strictly enforce spatial restrictions, or use a penalty function to discourage spatial restriction violations. Whereas the approach presented here is optimal, the algorithms are not necessarily optimal for implementing the approach. It is likely that some efficiencies could be added to the algorithms.

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SIMULATING LAND USE CHANGE AND ENVIRONMENTAL IMPACTS

Li-Ta Hsu and Walter L. Mills, Jr.[1]

ABSTRACT.—A binary-logit probit model of the conversion of farmland and forest land to urban use was estimated. This land use choice model was then used to simulate future land use changes under different scenarios. Factors considered in the models included soil characteristics, location, land tenure, size of parcels, zoning and other regulations, and level of urbanization. Spatial data and relationships are modeled in the land use choice model by including soil conditions, proximity to urbanized areas, and travel time. Five scenarios—basic, wetland protection, riparian protection, traffic improvement, and equal probability of development—were simulated.

INTRODUCTION

Maintaining healthy ecosystems and protecting the earth's biological diversity has recently aroused significant concerns (Costanza *et al.* 1992). Scientific evidences suggest that the present-day extinction rate is at least hundreds of times higher than the long-term natural rate (Myers 1988); and, if current trends continue, 2.5 percent to 15 percent of all species on earth could be lost over the next decade (Primack 1993). Among the many factors contributing to loss of biological diversity, the most threatening one is loss of habitat (Primack 1993). Alteration of natural environment by human activities has caused unprecedented loss of species and degradation of ecosystems. Human activities such as farming, ranching, and urban development have converted natural landscapes into mosaics of natural vegetation within matrices of human-dominated land uses and have had a profound impact on species and ecosystems (Adams 1994).

From humans' perspective, however, alteration of natural landscapes reflects their need for food, shelter, and many other natural resources (Barlowe 1978). Humans respond to these needs under various natural, economic, and social constraints and behave to increase both economic and sociocultural well-being (Rebisame *et al.* 1994). As a result, human land use patterns that affect ecological phenomena or alter the natural environment are driven by a variety of social processes (Rebisame *et al.* 1994). Therefore, to better understand the impact of land use change on terrestrial ecosystems, the social processes, and factors affecting human land use must be more fully studied (Machlis and Forester 1996). In recognition of the importance of social processes, the National Research Council stated that "biological diversity has been lost as a result of social processes, and will ultimately be conserved only through adjustments in these processes. Unless and until they are understood, there is little lasting hope for conservation" (National Research Council 1992, page 8). The Nature Conservancy, in its Last Great Places initiative, also recognized that "the continued success of our efforts to preserve biodiversity in the face of mounting threats will depend on our ability to integrate socioeconomic factors into our conservation equations" (Watson 1994, page 33).

OBJECTIVES

The socioecological interrelationship has been widely recognized, and several conceptual models have been developed to depict the complex interactions between humans and the natural environment (e.g., Messerli and Messerli 1978, Vink 1983, Turner *et al.* 1994). These models generally recognize the importance of social forces on the natural environment and interpret landscape or land use as the interface between natural and social processes. In van Langevelde's (1994) framework, landscapes should be perceived as the total spatial and functional entity in which social processes or human practices interact with natural processes. Turner *et al.* (1994) indicated that there is a crucial need for a better understanding of the human forces driving ecological change. However, until recently, studies on the subject of socioecological interaction rarely go beyond conceptual discussion (Machlis and Forester 1996).

To make the conceptual models operational, a practical methodology is necessary. The recognition of land use as

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the socioecological interface leads to the need for land use study. Land use study is an interdisciplinary research field related to ecology, geography, economics, and sociology. Studying the processes of land use and land use change can help to understand the connection between social processes and the natural environment. Therefore, the objectives of this study are:

1. To study the processes of human land use and to develop models for explaining and predicting land use changes.

2. To present a method that integrates human land use processes and environmental or ecological impacts.

To illustrate the proposed methodology, an analytical framework was applied to a case study of an urbanizing watershed. The case study focused on landscape changes resulting from urbanization. Urbanization has been described as a "convenient shorthand for the ecological forcing functions created by the growth of cities and associated human activities" (McDonnell and Pickett 1990, page 1232). Ecologically, urban areas are effectively synonymous with ecosystem disruption and erosion of biological diversity (Murphy 1988). From a sociological perspective, urbanization also represents a complex social process closely associated with many other social issues such as employment, welfare and poverty, education, and crime (Mills 1972, O'Sullivan 1990).

PROCEDURE

Study Area

The study area is a small watershed adjacent to the western boundary of West Lafayette in Tippecanoe County, Indiana. The watershed covers 27.8 square miles and Indian Creek flows 10 miles from north to south into the Wabash River. In order to obtain landowner property boundaries, the public land survey system of sections and townships is used to approximate the watershed boundary. The study consists of the 41 sections.

Land uses in the study area were classified into three categories: agricultural, urban, and public and others. Although agriculture has been the dominant land use, urban influence is spreading westward from the city of West Lafayette. The percentage of urban land uses increased from 8 percent in 1989 to about 12 percent in 1995. Urban land uses were primarily residential; industrial and commercial developments were relatively few. The category "public and others" includes areas designated for public services such as parks, golf courses, utilities, and cemeteries. It also includes 2,059 acres of land held by Purdue University.

Data Collection

Data collected for the empirical analysis came mainly from the geographical information system (GIS) database of Indian Pine Natural Resources Field Station, property records maintained by Tippecanoe County Offices, and the soil survey of Tippecanoe County from the Natural Resource Conservation Service of the United States Department of Agriculture. The Indian Creek watershed is one of the watersheds within the boundary of the Purdue Indian Pine Natural Resources Field Station. The Indian Pine Natural Resources Field Station was organized in 1989 by Purdue University to examine ecological processes in human dominated landscapes. The GIS database contains digitized maps (mostly in 30x30 m resolution) including ownership boundaries and other spatial data. The GIS ownership boundaries were matched with the property records maintained by Tippecanoe County. As of December 1995, a total of 2,396 land parcels were identified within the study area. The property records were then traced back to the year 1989 to identify any land use change during the period of 1989 and 1995. Subsequently, 631 agricultural land parcels were identified as present in 1989. Among them, 127 (or 20 percent) of the parcels were either converted to urban uses or idle awaiting for urban development during the observed 6-year period.

From the 631 agricultural land parcels (as of 1989), 250 were selected for more detailed data collection. To maintain representative proportions observed in the overall agricultural parcels, 50 parcels (20 percent of the 250 parcels) were randomly selected from those parcels that switched all or part of the parcel to urban use during 1990 and 1995. The other 200 parcels were randomly selected from those parcels that remained in agriculture throughout the observed period.

Characteristics of land ownership, including parcel size, frequency of land transfer, existence of land improvement, address of the landowner, and zoning regulations for the 250 sample parcels, were collected from county property records. Regional development trends were represented by the total housing units in West Lafayette and its fringe areas. Local development trends were summarized as the percentage of urbanization in a section and a quarter-section based on the property records. Land characteristics and spatial attributes such as soil productivity, building suitability, acreage of woodland in the parcel, traffic time to the nearest business center, and accessibility to sewer systems were derived from the GIS database. As a result, data for the 250 parcels at 6 points in time were established. The land use data and the observed variables of the 1,500 observations (250 parcels times 6 years) were subsequently used to examine the relationship between the urbanization

decision and the characteristics of land and land ownership. Table 1 summarizes the definitions of variables and their expected effects on urbanization.

Analytical Framework

The first step in this study was to develop a land use choice model for explaining observed urbanization pattern and predicting future urbanization probabilities for agricultural land. The land use choice model assumed that landowners make land use decisions by maximizing their utilities from land uses. That is, an agricultural land will be converted to urban uses if the landowner perceives a higher satisfaction from converting to urban uses than remaining in agriculture use. The utility functions of different land uses were assumed to be dependent on a set of observed variables and other unobserved random errors. A binary logit model was used to empirically derive the relationships between urbanization decisions and the observed explanatory variables. Factors examined are those listed in Table 1. The binary logit model was specified as

$$(1) \qquad y^*_{it} = \beta^{l} \, ' \, x_{it} + \varepsilon_{it} (i = 1 \ldots 250, t = 1 \ldots 6)$$

where y_{it} is the land use choice ($y_{it} = 1$ if the parcel was urbanized and $y_{it} = 0$ if the parcel remained in agriculture), and y^*_{it} denotes the utility differences between urban uses and agricultural uses ($y_{it} = 1$ if $y^*_{it} > 0$ and $y_{it} = 0$ otherwise). x_{it} is a vector of observed exogenous variables relevant to land use utilities. β^{l}_{it} is a vector of parameters associated with the exogenous variables. ε_{it} is an unobserved random error term. Assuming the relationships continue to hold in the future, the binary logit model can be used to predict urbanization probabilities of the remaining agricultural parcels. The urbanization probability of land parcel i at time t is

$$(2) \qquad P_i = \frac{\exp(\beta' x_{it})}{1 + \exp(\beta' x_{it})}$$

The second step of the case study was to project urban growth in the study area for the next 10 years. Housing-unit growth from 1989 to 1995 in West Lafayette and its fringe areas were fitted with regression-based growth projection models to estimate the growth rate, and to test whether the arithmetic growth model or the exponential growth model is more appropriate. The results showed that West Lafayette and its fringe areas had an arithmetic growth trend with an estimated annual growth rate of 1.745 percent. The same growth rate was used to project future urban development in West Lafayette and its fringe areas. Future urban development in the study area was projected using a ratio-based technique that predicts the urban development in the study area as a proportion of the urban development in West Lafayette and its fringe areas. Based on the property records of the study area, the ratio increased from 8.1 percent in 1989 to 9.7 percent in 1995, and is expected to increase to 12.3 percent in 2005 if the trend continues. Table 2 shows the projected urban growth in West Lafayette and its fringe areas, and for the study area from 1995 to 2005.

Table 1.—*Explanatory variables and their expected effects on urbanization*

Variable	Expected influence	Definition of Variables
TIME	-	Traffic time to the nearest business center (in minutes)
SEWER	+	Whether the parcel is within 1000 feet of sewer systems (1=Yes, 0= No)
PROD	-	Soil productivity of the parcel (in bushels of corn per year)
BLDG	+	Building suitability of the parcel
IMPROV	+	Existence of land improvements (1=Yes, 0= No)
FOR	+	Acreage of woodland in the parcel
SEC	+	Percentage urbanized in the section
QTR	+	Percentage urbanized in the quarter section
DWELL	+	Number of dwelling units in West Lafayette and its fringe areas
URBAN	+	Whether the parcel is located within the urbanizing boundary (1=Yes, 0= No)
ZONING	?	Whether the parcel is zoned for urban uses (1=Yes, 0= No)
ACRE	-	Acreage of the parcel
TRANS	+	Number of land transfers since 1981
ADDR	?	Whether the landowner lives in Tippecanoe county (1=Yes, 0= No)

Table 2.—*Projected regional housing developments and housing units within the study area*

Year	West Lafayette and its fringe areas	Study area
1995	17261	1676
1996	17534	1748
1997	17806	1822
1998	18079	1897
1999	18351	1974
2000	18624	2052
2001	18897	2132
2002	19169	2213
2003	19442	2295
2004	19715	2379
2005	19988	2464

The third step of the study was to allocate the projected urban growth spatially and temporally to the study area. The estimated binary-logit land use choice model was used to predict the urbanization probabilities of the remaining agricultural parcels in the study area. Parcels to be urbanized were selected based on the relative probabilities of the parcels. Parcels with higher urbanization probabilities are more likely to be urbanized. The urbanization probabilities were updated in each year of the simulations. Since urbanization of any land parcel was only known probabilistically, different runs of the simulation would generate different urbanization patterns. Therefore, the simulation process was repeated 1,000 times to generate distributions of simulation results.

Urbanization impacts including acreage of forests and wetlands affected by urbanization, changes in annual agricultural production, and urbanization impacts on surface-water run-off were also monitored in the simulated urbanization process. Forests and wetlands affected by urbanization were derived from the simulated urbanization patterns and maps of existing forests and wetlands. There are about 3,280 acres of forests and 709 acres of wetlands in the remaining agricultural land. Changes in agricultural production were derived from the acreage of croplands being urbanized and soil productivity. Effects on surface-water run-off were evaluated in terms of changes in the curve number of the watershed. The watershed currently has a composite curve number of 77. The curve number is an empirical overall rating of land based on soil hydrologic grouping and land use. It can be combined with long-term climatological data to predict surface-water run-off from given rainfall depths (USDA SCS 1986, Harbor 1994).

To compare urbanization impacts under different situations, five land use scenarios were simulated.

1. A **basic** scenario simulating urbanization patterns under existing conditions;

2. An **equal-probability** scenario that assumes that all parcels have the same probability of being urbanized and results in uniformly random urbanization patterns. This scenario was used to compare the differences between uniformly random urbanization patterns and patterns based on the predicted urbanization probabilities.

3. A **wetland-protection** scenario protects remaining wetland by prohibiting urban development.

4. A **riparian-protection** scenario protects stream and riparian areas by restricting urbanization within a 100-foot riparian buffer zone. Parcels affected by the buffer zones were mainly those adjacent to the upper streams because riparian zones in the lower section of the watershed were generally zoned as flood plains where urban development is already prohibited

5. A **traffic-improvement** scenario modeling proposed traffic improvements in the southern part of the watershed. The traffic improvement changes the travel times, increasing urbanization probabilities.

RESULTS

Parameters of the binary-logit model were estimated using the maximum likelihood method. Several variables were found to have diminishing influences on choice probabilities. For these variables (ACRES, FOR, SEC, TRANS), square-root or logarithm transformations were made to account for the diminishing effects. Multicollinearity between variables was found to be an estimation problem in the logit model. There was a high correlation between traffic time (TIME) and urbanizing boundary (URBAN), between soil productivity (PROD) and acreage of woodland in parcel (FOR), and between zoning (ZONING) and sewer accessibility (SEWER). As a result, some of the estimates of the coefficients in the full model were biased. Therefore, three of the explanatory variables (URBAN, PROD, and SEWER) were excluded so that the influences of the remaining variables might be determined. The estimation results of the logit model were shown in table 3.

Measures of the goodness of fit indicate that the model fit the data fairly well. The likelihood ratio test statistic, which is asymptotically distributed as χ^2 with K degrees of freedom (K = number of parameters being estimated), rejected the null hypothesis that all the parameters are zero, suggesting that there is a relationship between the urbanization probability of a parcel and the explanatory variables. The likelihood ratio index (ρ^2) is an informal

Table 3.—*Estimation results of land use choice models*

Variables	Parameter estimates	Asymptotic t-statistics
Constant	-10.478	-2.493
TIME	-0.18663	-3.254
BLDG	1.9405	4.960
IMPROV	0.44667	2.050
SQRT(FOR)	0.39065	4.620
SQRT(SEC)	-0.41405	-3.768
SQRT(QTR)	0.36257	5.387
DWELL	0.62941	2.420
ZONING	-0.58038	-2.219
ln (ACRE)	-0.91640	-6.069
SQRT(TRANS)	1.3709	6.595
ADDR	1.1819	2.985
Likelihood Ratio Test Statistic	329.133	
Likelihood Ratio Index (ρ^2)	0.3453	

goodness-of-fit index that measures the fraction of an initial log-likelihood value explained by the model. ρ^2 ranges from zero, when the estimated parameters are no better than zero parameters, to one, when the estimated parameters allow for perfect prediction of the observed choices. However, the likelihood ratio has no intuitively interpretable meaning for values between the extremes of zero and one, and there are no general guidelines for when a ρ^2 value is sufficiently high. Nevertheless, when comparing models estimated on the same data and with the same set of alternatives, it is usually valid to say that the model with higher ρ^2 fits the data better.

The effects of explanatory variables in general agree with the a-priori expectations. Results of the logit land use choice model indicate that several factors might have contributed to the observed urbanization patterns of agricultural land in the study area. Large parcels and parcels farther away from business centers were less likely to be urbanized. Parcels with land improvement or higher building suitability, parcels containing large acreages of woodlands, parcels owned by local landowners, and parcels undergoing frequent land transfer were more likely to be urbanized. Regional and local development trends also positively contributed to urbanization decisions. Probability of urbanization increased as the percentage urbanized in a quarter-section increased, but the effect diminished as the section became more densely developed. Zoning was found to have a negative effect on urbanization decisions, suggesting that speculation existed in areas zoned for urban uses. The speculation effect explains the leapfrog urbanization pattern found in the study area.

Based on the simulated urbanization patterns, urbanization impacts under each scenario were evaluated. Table 4 summarizes the means of urbanization impacts under different simulation scenarios. Duncan's multiple-range tests (Duncan 1955) were used to perform pairwise comparisons to test whether the means are significantly different between the scenarios.

Figure 1 compares the distributions of urbanization impacts of the five land use scenarios. Environmental impacts of the equal-probability scenario appear to be significantly different from the others. That is, if different parcels do have different urbanization probabilities, ignoring such differences would significantly overestimate the total urbanization acreage as well as changes in agricultural production and curve number, while underestimating urbanization impacts on forests and wetlands. Some of the environmental impacts of other scenarios are also statistically different from those of the basic scenario. Protecting wetlands from urban development would significantly reduce urbanization impacts on forests, wetlands, and curve number, but at the expense of greater agricultural loss. Riparian protection also has similar effects, but the effects are less significant. Proposed traffic improvement, if completed, would increase urbanization acreage, slightly decrease impacts on wetlands, slightly increase agricultural loss, but would not significantly affect impacts on forests and changes in curve number. However, forests affected by urbanization in the basic scenario and traffic improvement scenario have different spatial patterns although they are quite similar in terms of acreage.

CONCLUSIONS

Several conclusions can be drawn from the findings of this case study. First of all, land use patterns in human-dominated landscapes are not completely random. Land use patterns not only depend on characteristics of land, but also depend on land use regulations, regional and

Table 4.—*Comparison of urbanization impacts under different simulation scenarios*

Means of impact (with 1,000 simulations)	Basic scenario (B)	Wetland protection (W)	Riparian protection (R)	Traffic improvement (T)	Equal probability (E)	Duncan's[a] multiple range test[b]
Acreage of urbanization (acres)	2,077.76	2,077.76	2,070.95	2,097.69	2,159.33	RBWTE
Forests affected by urbanization (acres)	611.38	575.47	593.92	611.53	370.46	EWRBT
Wetlands affected (acres)	62.49	0	58.26	60.99	38.73	WERTB
Agricultural reduction (1,000 bushels of corn)	169.26	173.29	170.58	171.19	220.12	BRTWE
Decreases in watershed curve number	0.531	0.553	0.537	0.530	0.660	TBRWE

[a] DUNCAN, D.B. 1955. Multiple range and multiple F tests. *Biometrics*. 11:1-42.
[b] Scenarios are listed from left to right in ascending means of impact; scenarios whose impacts are not significantly different are underlined.

local development trends, and characteristics associated with landowners. Second, different land parcels have different land characteristics, and they may be owned by different landowners or subject to different land regulations. As a result, different land parcels may have different probabilities of land use change. Failure to account for the probability differences may result in erroneous predictions of land use patterns and land use impacts. Third, human behavior is inherently probabilistic, and, as such, land use patterns in human dominated landscapes can only be predicted probabilistically. However, with the probabilities of land use change derived from land use choice models, likely land use patterns and distributions of land use impacts can be simulated using repeated simulations. The simulation approach can be used to incorporate ecological or environmental assessment with human land use activities, and is useful in comparing the effects of different land use control strategies and in deriving the relationships between land use changes and land use impacts.

There are always tradeoffs between human needs and ecological or environmental protections. Since different land use patterns may result in different land use impacts, human impacts can be minimized by selection of an "ideal" land use pattern. In reality, the ideal land use pattern probably will not be automatically achieved because land use impacts are seldom included in landowners' land use decision. However, a better understanding of land use dynamics can provide insights into the search for sustainable development and sustainable ecosystems. While actual land use patterns do not always agree with the expectation of land use planning, land use regulations and provision of public services do affect land use patterns and land use impacts. A better understanding of the mechanisms of land use change are needed to properly design public regulations and/or services that will achieve public goals.

This study presented a land use choice model and a simulation framework that can be used to interconnect human land use activities and environmental impact assessments. Land use change can be explained as a social process in which landowners make land use decisions based on their preferences. Therefore, land use choice models, which explain land use choices based on landowners' utility maximizing behaviors, are appropriate for modeling land use change in human-dominated landscapes. Social and environmental factors, as well as their interactions, can be integrated into land use choice model to explain land use patterns.

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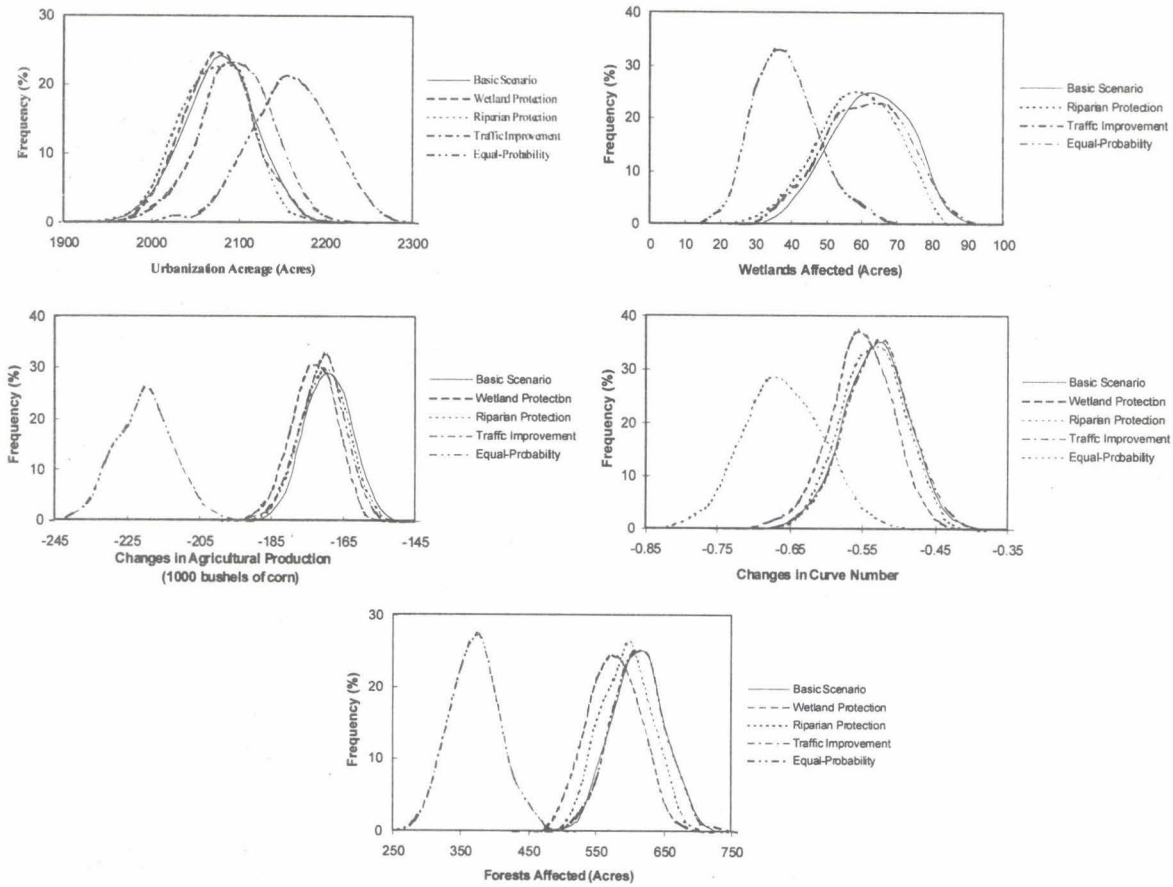

Figure 1.—*Comparison of urbanization impacts from the different land use scenarios.*

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GIS-BASED MULTICRITERIA APPROACHES TO LAND USE SUITABILITY ASSESSMENT AND ALLOCATION

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ABSTRACT.—Land suitability assessment in a Geographic Information System (GIS) environment is formulated as a multi-criteria decision making (MCDM) problem. Different MCDM approaches are developed to combine factors in a suitability analysis of land for potential land uses. These MCDM approaches are used to develop a generic suitability index. Approaches include both qualitative and quantitative techniques. Results from the MCDM analysis are then linked to a GIS for more detailed spatial analysis. Besides land suitability evaluation, an MCDM framework is also developed for land use allocation. The framework captures the multi-criteria nature of land suitability analysis and at the same time allocates land by maximizing the overall suitability of a land area.

INTRODUCTION

This paper addresses two critical issues in land use planning; land use suitability and land use allocations. Land use suitability is a generic term associating a combination of factors and their impacts with respect to potential land uses. Land allocation, on the other hand, involves the process of designing an optimal mix of land uses based on their estimated suitability and perceived management objective.

The objectives of this paper are: (1) to develop multi-criteria approaches in evaluating land use suitability; and (2) to use different measures of land use suitability as guides to optimally allocate lands to their most suitable uses. Moreover, the paper also aims to develop an integrated model that accommodates these objectives in a spatially explicit planning and decision making environment through the use of a Geographic Information System (GIS).

An integrated GIS-based multi-criteria approach to land suitability analysis and allocation offers significant advantages. The GIS environment enables the spatially explicit evaluation of site suitability and the assignment of various measures of suitabilities to specific sites or geographic areas. The integration also allows area allocations at specific spatial or geographic locations. Hence, the integrated GIS-based model combines the spatial capabilities of GIS, with the analytical power of multi-criteria analyses. That is, the GIS-based integrated model permits both analytical planning and optimization of land use decisions at different levels, namely; (1) site suitability assessments based on different factors and specific land uses; (2) generation of suitability indices based on combinations of different factors (i.e., composite index/measure of site suitability); and (3) generation of an optimal land use plan that simultaneously considers the individual site suitabilities, and the optimal allocation to the most suitable land use (i.e., mix of land uses that yields the "highest" overall cumulative suitability.

SITE (LAND) SUITABILITY ASSESSMENTS

There is a significant amount of literature dealing with land suitability assessments. Anderson (1987) surveyed different methods of land capability/suitability analysis ranging in degrees of computational and analytical sophistication. Hopkins (1977) reported a comparative evaluation of alternative methods of assessing land use suitabilities. More recently, Steiner (1983, 1987) reviewed land evaluation and site assessment (LESA) using USDA-recommended standards.

Site suitability assessment is inherently a multi-criteria problem. That is, land suitability analysis is an evaluation/decision problem involving several factors. In general, a generic model of site/land suitability can be described as:

$$(1) \quad S = f(x_1, x_2 \ldots, x_n))$$

where S = suitability measure; x_1., x_2, ..., x_n = are the factors affecting the suitability of the site/land.

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The principal problem of suitability analysis is to measure both the individual and cumulative effects of the different factors; $x_1, \ldots, x_n$. In other words, suitability analysis generally involves determining an appropriate approach to combine these factors. Some approaches to combining these factors include: (1) composite rating, including weighted composite ratings (Anderson 1987); (2) weighted factor method (Hopkins 1977); (3) various forms of multi-criteria approaches such as compromise programming (Pereira and Duckstein 1993), Prioritized Land Use Suitability (PLUS) by Xiang and Whitley (1994), use of effectiveness matrix (Jankowski and Richard 1994), modified weighted factor (Diamond and Wright 1988); and (4) the heuristic rules of combination expressed through verbal logic rather than in numeric terms (Hopkins 1977).

Another classical site suitability analysis approach is through formal functional relationships of the different factors. Most notable among these approaches is regression analysis. Wildlife habitat suitability assessments, for example, commonly use a regression analysis procedures to estimate habitat suitability indices (Pereira and Itami 1993).

SUITABILITY ANALYSIS AND ANALYTIC HIERARCHY PROCESS

This paper proposes an alternative approach to site suitability analysis. Most of the suitability analysis techniques described above rely on significant amounts of information to be useful, applicable, and effective. Regression analysis, for example, will require a cross-sectional database covering the wide range of suitability conditions as affected by the different factors individually and collectively. If such data are available, formal analysis of the composite function in (1) such as regression analysis, is warranted and also offers an accurate way to evaluate site suitability. If, on the other hand, data are incomplete, or if significant information gaps exist in the cross-sectional database, then it may be more appropriate, practical, or convenient to adopt an alternative approach that does not rely on complete or comprehensive databases. One such approach is the Analytic Hierarchy Process (AHP).

AHP offers some advantages over the classical site suitability analysis techniques. First, it provides a structured approach to measuring suitability by "decomposing" the suitability analysis problem into hierarchical units and levels. This allows a systematic and more in-depth analysis of the factors which may be better understood when "de-coupled" or "deconstructed" into their lower and more specific forms or indicators. Second, AHP relies less on the completeness of the data set, and more on "expert" opinions or observations about the different factors and their perceived effects on site suitability. Third, the approach is more transparent and hence more likely to be accepted especially when the suitability analysis will ultimately serve as a basis for land allocation. Fourth, AHP allows for the participation of both experts and stakeholders in providing the suitability measure of a site relative to a proposed land use. Such framework allows the incorporation and accommodation of both qualitative and quantitative criteria for assessing site suitabilities.

AHP is well documented in a significant number of published literature (Mendoza *et al.* 1989; Mendoza 1997; Saaty 1980, 1995; Kangas 1992, 1993; Peterson *et al.* 1994; Reynolds and Holsten 1994; Pukkala and Kangas 1996) and will not be described in this paper. AHP applications to suitability analysis are reported in Banai-Kashani (1989); Eastman *et al.* (1992, 1993); and Xiang and Whitley (1994).

GIS-BASED MULTI-CRITERIA METHODS

GIS is a computer-based system that offers a convenient and powerful platform for performing land suitability analysis and allocation. As pointed out earlier, the integration of multi-criteria methods of suitability assessments and allocation methods into a GIS system offers both the spatial capabilities of GIS and the analytical power of formal multi-criteria decision making tools.

The site suitability analysis approach proposed in this paper takes a generalized form of (1) as follows:

$$S = \sum_{j=1}^{n} c_j x_j \qquad (2)$$

where: x_j = are the factors affecting suitability;
c_j = are "parameters" associated with each factor.

Note that the simple model described in (2) is linear. Given a sufficient dataset, the c_j's can be easily estimated, and subsequently determine S. However, in many suitability analysis cases, a complete cross-sectional database for all x_j's are not available, nonexistent, fraught with errors or uncertainty, and difficult, costly, or even impossible to generate. Alternatively, one could estimate the c_j's not through an information-intensive procedure like regression, but through systematic analysis of information obtained from experts, users, and other stakeholders who are most informed about the site and its suitability for a potential land use. Such information is generated through structured questioning designed to elicit the experts' judgment and opinion. Results from this structured questioning and the resultant matrix of

information that reflect the experts' judgment and opinions form the basis for estimating the parameters in c_j. Hence, c_j's are viewed not as technical coefficient associated to each factor; instead, they represent the relative importance or degree of influence of each factor to the overall measure of site suitability. In this case, c_j are estimated not through formal parameter estimation procedures like least squares in regression, but through AHP. It should be noted also that the c_j's estimated by AHP reflect the relative weights of each factor which are scaled and normalized. Hence, they are somewhat analogous to the set of scaled and normalized set of regression coefficients.

The model described in (2) can be easily transformed and implemented in a raster GIS environment (Eastman *et al.* 1995a, b). Current GIS functionalities and capabilities can computationally operationalize the model in (2) using Map Algebra.

GIS Suitability-based Land Allocation

The proposed integrated GIS-based model can provide more than site-specific and spatially explicit map of site suitabilities. The integrated model can also use these site suitabilities to serve as a guide to subsequent allocation of land to potential uses. This allocation process is performed and implemented under a raster GIS environment.

Recently, there have been attempts to combine GIS with optimized land allocation techniques. In most of these, integration is achieve sequentially or in a linear fashion; that is, optimized allocation is performed independently using various types of optimization models, then the results of the optimization is exported to a GIS for mapping and display (Jones *et al.* 1995, Church *et al.* 1995, Chuvieco 1993, Campbell *et al.* 1992, Carver 1991, Diamond and Wright 1988). While this approach is plausible in some applications, an alternative approach is to impose the integration simultaneously rather than sequentially. That is, the site suitability estimates serve as the defining variables for land allocation. Hence, optimized allocation is done internally within the GIS system.

Before describing the multiple land use allocation model proposed in this paper, the discussion below outlines the methodology for land allocation under a raster-based GIS platform considering one land use. That is, individual cells/pixels are allocated to a single land use given their land suitability values. The model can be described as:

(3) Maximize ΣS_k for all k
Subject to: $\Sigma a_k = A$

where S_k is the suitability index for pixel/cell k, a_k is the area of cell k, and A is target area allocation.

This seemingly simple model is quite difficult to implement within a GIS system. To accomplish this, Eastman *et al.* (1995a, b) devised a heuristic procedure that achieves the optimized allocation in (3). The procedure simply involves ranking of all the pixels/cells based on their S_k values. In other words, an image (i.e., derived map) can be generated containing the "ranked" values of each cell. That is, the values of each cell in the image (S'_k) is "transformed" from each original suitability value (S_k) where the transformed value reflects its "rank" among all cells. The number of cells to allocate to the land use (according to its suitability value) will depend on the target allocation, A, and the resolution of the pixel/cell. But, the "optimized allocation" is made by systematically selecting from highest ranked cells to lower ranked cells.

The model described in (3) allocates cells/pixels based on their suitability values for a single land use. The real problem in land use planning, however, involves the allocation of tracts of lands or sites into alternative land uses. This becomes most problematic when the land could be allocated to various land uses some of which are complementary while others may be competing. Further complicating the allocation problem is the involvement and potential pressure exerted by interest groups or stakeholders with vested interests on how the land is allocated. Thus, the allocation problem becomes not only a multi-factorial land use suitability problem, but also a multiple-objective, multi-decision maker land allocation problem.

A multiple land use allocation model based on suitability values can be formulated by expanding the model described in (2). Clearly, for a given land use, one could implement models (1) and (2) to generate a suitability map for the particular land use. Hence, suitability maps reflecting the suitability values of each pixel relative to a particular land use can be generated using (2) and (3). The use of AHP insures that the suitability maps are comparable for all land uses (i.e., they are scaled and standardized because the c_j's in (2) are normalized.)

Allocation of land to alternative uses must address the following issues: (1) Each pixel/cell has different suitability value associated to a particular land use; (2) Land uses are either complementary (i.e., compatible) or competing (i.e., exclusive); and (3) Stakeholders, interest groups, or decision makers value each land use differently.

Suitability maps as described above address the first issue. These reflect the suitability values of each pixel/cell calculated by (2) given the c_j's estimated by AHP.

The second issue actually involves two interrelated problems. The first problem must consider the fact that land uses have different degrees of importance, or relative values to different interest groups or stakeholders. The second problem involves the manner of "combining" these different valuations of relative importance for each land use. Hence, the second issue then requires some mechanism to, not only evaluate the relative importance of each land use, but also to collectively arrive at a compromise valuation that is consistent and acceptable to the stakeholders. These two problems and the proposed mechanism to solve them are described in more detail in the next section. Again, in this context, the AHP offers a transparent and convenient procedure for achieving both.

The third issue relates to the participation of various stakeholders in the evaluation of land uses and subsequent land allocation. Studies have shown that land use planning and allocation are best achieved under a participatory framework where stakeholders play significant roles in the decision making process. The AHP approach offers both structural and procedural features that accommodates the evaluation and decision making requirements of such a participative framework.

Briefly, AHP can be used to generate the relative weights or degree of importance of each land use. Given these weights, one could formulate a general optimization problem as:

$$(4) \qquad \text{Max } \mathbf{Z} = g(S_1. S_2. \ldots,.Sp) \quad \text{s.t. } x \varepsilon X$$

where **Z** is an indicator of overall cumulative suitability; S_1. S_2, ..., Sp are the generic measure of suitability for each land use (i.e., suitability maps). Clearly **Z** could be a vector, or a scalar depending on how land use utilities are combined in an attempt to forge a compromise valuation of all land uses. The simplest case would be to devise a "composite measure" where **Z** is a single value denoting the overall cumulative utility. That is;

$$(5) \qquad Z = \Sigma w_k Z_k$$

where w_k, are the relative weights generated by AHP for each land use.

Optimizing Land Use Allocation Within GIS

The procedure for optimizing land use allocation will depend on whether the land uses are compatible or conflicting. First, consider the case when the land uses are compatible. This is a simple land allocation case because technically, if all the land uses are compatible, then there is no pressure to allocate the land for alternative land uses. The allocation is simply based on a descending measure of overall (i.e., composite) or cumulative suitability for the compatible land uses. Procedurally, this is similar to allocation when there is only one land use. In other words, the ranked-based allocation will be based on the cumulative measure Z described in (5) which actually combines the individual suitabilities for each land use as described in (3).

The models described in (2)-(5) achieve optimal single land use allocation within GIS through the heuristic procedure based on ranking of each cell according to their suitability values. The constraint set in (4) is essentially target allocations as described in (2). However, in many cases, there are other constraints that must be satisfied simultaneously. While this is easy to perform in most mathematical programming models, achieving this spatial allocation optimally while considering all constraints simultaneously, is a more difficult task. Another heuristic procedure developed by Eastman *et al.* (1995a, b) achieves this simultaneous constraint satisfaction by modifying the suitability measure as described below:

$$(6) \qquad Z = \Sigma w_j x_j * \Pi_i c_i$$

where the c_j's are the constraint "scores" which are either zero-or-one. In other words, Boolean images could be created to represent each constraint, where the Boolean image has a value 1 for reclassified cells that satisfies the constraint, and 0 otherwise. By "modeling" these Boolean images representing the constraints, only those cells that satisfy all constraints (non-zero), will be considered in the allocation. Those cells that have at least one zero value (because of at least one constraint not being satisfied), will have a zero multiplicative value, and hence, it is assigned a zero suitability.

The optimal land use allocation procedure is a bit more complicated when the objectives are conflicting. In this case, land use allocations are exclusionary; that is, a piece of land can be allocated to only one land use. There are two possible ways to solve the problem. One is through a "prioritized allocation." That is, the land uses are compared in terms of priority. Single land use allocation is done first to the land use rated as the highest priority following the procedures described previously. Then, allocation of remaining cells is done for lower priority land uses. This approach assumes that higher ranked land uses are infinitely more important, and that no trade-off between land uses is allowed.

The other approach is to develop some "compromise allocation" based on some versions of compromise programming. The simplest approach would be to use the method developed by Eastman *et al.* (1995a, b) where allocation to competing land uses is done through the "minimum" Euclidean distance to the "ideal". That is, a

"metric" is devised representing the distance of the suitability of each cell relative to the maximum suitability of the different land uses. Cells are allocated to the land use "closest" to the ideal value of each land use.

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REGIONAL MODEL FOR RURAL LAND USE PLANNING: AN APPLICATION OF GOAL PROGRAMMING

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ABSTRACT. —Strong demand for firewood and construction material in the urban areas of Mozambique, especially Maputo city, coupled with slash and burn agriculture, has led to an increase in deforestation. As a measure to mitigate this and other problems facing the forestry sector, the government designed what is known as Strategies for Forestry Development (1991) which includes a reforestation strategy. This contemplates the involvement of the community as a way forward for afforestation since the government has limited funds to embark in large-scale reforestation programs. This paper reports the results of a study which explored the potential for using Weighted Goal Programming (WGP) in assessing the impact of integrating trees into the farming systems in the province of Maputo. Models of typical farms from five ecozones were constructed and aggregated in an effort to assess the impact of the reforestation strategy, at provincial (macro) level, while focusing on the use of resources at the household (micro) level. Despite the scarcity of data and political and climatic instability, which influenced the quantity and quality of data, the planning framework results show that all regional goals can at least be achieved. Land use is predicted to change in all ecozones with regard the land allocation to individual crops. Furthermore, allowing each typical farm to be able to plant at least one hectare with trees was found to be possible, but with some changes in the level of performance of the current farm activities. In addition to income generation, the reforestation strategy was found to reduce adult underemployment, especially in the grassland ecozone, however, in some ecozones it implied the use of more child labor. There is potential for applying mathematical programming in land use conflict resolution in a data scarce environment.

INTRODUCTION

In many developing countries, clearance of forestry resources for construction and energy supply in urban areas accompanied by slash and burn agricultural practices, has resulted in deforestation. In Mozambique, and particularly the Maputo province, (the capital city of which is home to a large portion of the national population), such a situation led the government to design what is known as the Strategies for Forestry Development (1991) which includes a Reforestation strategy. This states that the community should participate in the replacement of the forest resources extracted in order to guarantee their sustainable use. In some zones, such a strategy has been implemented without previous appraisal of the relevant technical and socio-economic issues involved. The result was a significant underachievement of the projects' aims in terms of tree survival rate and management of plantations, either in woodlots or in intercropping systems. Therefore, it can be argued that such situations arise as a direct result of introducing a tree component into existing agricultural systems without considering the potential conflicts such as labor availability and its allocation to the different farm activities.

This research attempts to use a relatively sophisticated *ex ante* planning approach, in a data scarce environment, to explore the mechanisms by which reforestation should take place. A modelling framework is constructed where both technical and socio-economic goals are incorporated to deal with the assessment of reforestation strategies under an integrated land use context. In this way, the study analyzes the impact of tree plantation in

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conjunction with already competing farm activities as well as conflicting household and regional goals.

The reforestation strategy is therefore a two-level decision problem involving the farm and the regional levels. Although the subject of this paper is focused on the latter, it incorporates constraints reflecting the activity of the former. The paper presents preliminary results of a regional model that aims to analyze the trade-offs among regional goals and their impact at the farm level in terms of land use, dietary issues, tree plantations, conservation and income levels.

MULTIPLE CRITERIA DECISION MAKING (MCDM)

Advances in science and computer technology questions the validity of the traditional single objective planning approach (Dent and Jones 1993) due to inadequacy of such criterion to represent satisfactorily the multiple objectives decision problems related with land use planning (Spronk and Matazarro 1992). The decision-maker (DM), at micro or macro level, generally looks for a compromise result, i.e., trade-offs among goals. Multiple criteria decision making methods (MCDM) take into account the various objectives of the DM and start with the definition of "best" which differs for each individual in the society. This, according to Kazana (1988), is the basic distinction between MCDM and linear programming (LP). Cohon (1978) also considers that multi-objective approaches assign adequate roles for both the analyst and the DM. In other words, the analyst generates alternatives and objective trade-offs while the DM makes value judgements about the relative significance of those alternatives.

With regard to the Reforestation strategy, implementation implies adoption of agroforestry systems by rural farmers in Mozambique. A survey conducted for this study showed that, in the case of the Maputo province, farmers have preference for village woodlots over intercropping. Kazana (1988) states that agroforestry systems in small farming systems in developing countries is mainly a decision making problem at a micro-economic level, because, also according to Janssen (1995), farmers control the use and management of the natural resources.

Therefore, a bottom-up planning approach appeared the appropriate procedure for this research. In order to do this, rural Maputo was classified into five ecozones based on existing land use, described by Saket (1994). A survey was conducted in each of these ecozones in order to elicit information regarding farm household objectives and constraints concerning food security, availability of fuel wood and wood for construction and income generation activities. Also, a survey of Maputo planning authorities was conducted to elicit the regional goals associated with the implementation of the reforestation strategy.

Goal programming (GP), one of the MCDM based on the geometric definition of "best" is regarded as a model which operationalizes the Simonian approach of "satisfaction" to the fulfillment of the DM's objectives (Rehman and Romero 1993 quoting Simon 1955, 1957). GP has two variants: Lexicographic Goal Programming (LGP) which is based on pre-emptive ordering of goals and priorities by the DM, and Weighted Goal Programming (WGP), based on a simultaneous consideration of goals and minimization of the sum of relative weighted undesired deviations from the targets. WGP was applied in the regional model, which is discussed further in the next section.

A criticism of the limited application of GP is the large amount of data required from the DM (including objectives, targets, weights, and priorities) and for estimation of the technical coefficients of the decision variables. This is a particularly important limitation in developing countries were planning in subsistence farming is made difficult due to a lack of record keeping of farm performance and where lack of coordination between agricultural and forestry extension services is likely to reduce the reliability of information provided by the DM. However, Rehman and Romero (1993) defend the application stating that sensitivity analysis can be used to generate information and reduce the amount of data needed from the DM.

METHODOLOGY

Introduction

In Maputo province there is a recognized energy problem due to high surplus demand of fuelwood. This is partly caused by the growing market in the urban areas. However, recent socio-economic, political and drought conditions led to the situation where the main source of survival for farmers was through exploitation of the natural forest, which provided a ready source of income. This is despite the fact that, according to existing forest legislation (MA-DNFFB 1987) the rural population can only exploit, for their consumption, third and fourth class species for poles and firewood without licensing. In the event of infringement, i.e., clear felling of trees with diameters greater than 30 cm for commercial purposes, fines ranging from US$52 to 155 can be charged. However, perhaps due to the recognition of the fact that forest products were the only source of farm livelihood during the civil war and drought periods, the government was passive in enforcing this legislation. The coexistence of these two issues (demand for income in the rural areas and demand for wood products in Maputo-city) led to

deforestation which resulted in some zones having fuel wood shortages even for local consumption.

Previous studies by Getahun (1991) and Bila (1992) and results of the survey for this study have shown that farmers recognize deforestation as a problem and tree plantation as a possible solution, as did the policy makers when they designed the 1991 Reforestation strategy. Therefore, this suggests that the apparent disparity in the definition of the problem facing the macro and the micro level of policy making, in other words, what Janssen (1995) calls aggregation of private and public rationale, may not be important. Consequently, it is hypothesized that solving farm level problems may simultaneously solve higher hierarchical level policy problems.

In this modeling approach, typical farm models are used as the basic building blocks of the regional model and are aggregated for Maputo province. These individual farm models allow us to understand how farmers' interact with the environment and thus what their likely voluntary response to policy will be, in order to meet their own goals, given land and labor resource limitations. The aggregation of the farm models is designed to model the overall farmer response to regional plans for meeting food and wood demands, as well as conservation policies for the natural forest within a regional budget constraint.

The Framework of the Regional Model

The Farm Models

The farm models representative of each ecozone comprise five main groups of decision variables: growing crops, selling surplus produce, purchasing food to offset deficits, nonfarming activities (NFA) (harvesting natural forest, carving, brewing, brick making) and tree plantation activities (PT) as shown in figure 1. In addition, the main constraints on these farm activities include land, seasonal labor, production reconciliation, diet balance, and NFA reconciliation.

Representative farms were selected from each ecozone classified in terms of similar cropping patterns and yields, same limitations in terms of inputs and technologies such as access to irrigation or not and alternative rural employment opportunities. Hazell and Norton (1986) state that simple rules like similar yields and similar technologies as well as similar land to labor ratios reduce aggregation bias and maintain a certain degree of conformity to Day's (1963) aggregation conditions. These include technological homogeneity, pecuniary proportionality, and institutional proportionality regarding, respectively, the same production possibilities, proportional returns, and proportional constraint vectors (in this case, land).

The "Regional Pool" Activities and Constraints

The aggregated surplus from each ecozone creates a common pool of activities at the regional scale. This permits interecozone trade, particularly of food products, to satisfy deficits in production of crops essential to the diet (fig. 1). The constraints and activities of this common pool comprise the total number of assumed homogeneous farms in each ecozone supplying the surplus of food, wood products, and construction materials to the "regional pool" (fig. 1) from which Maputo-city requirement is supplied (once aggregated interecozone trade is satisfied). This illustrates a realistic exchange of food products amongst ecozones, because there are markets in the rural areas which enable farmers from deficit zones (like dryland, grassland, and open forest) to purchase from surplus zones without having to travel to Maputo-city.

Regional Goals

A survey of staff at the Eduardo Mondlane University in Maputo, the Ministry of Agriculture and Fisheries and provincial and district agricultural officers, was conducted to elicit the goals of the reforestation strategy as viewed by these different planning entities. A summary of the ranked goals as perceived by these policy makers (PMs) is shown in table 1.

Table 1.—*Summary of the goals and the desired achievement function*

Goals variables	Targets	Deviational
Fuelwood (bags)	3,743,249	Minimize underachievement
Poles (m^3)	44,146	Minimize underachievement
Food (Kcal)	11,214,310,020	Minimize underachievement
Conservation (ha)	97,735	Minimize underachievement
Budget ($)	2,765,900	Minimize overachievement

Although policy makers provided the goal typology, values for respective targets were estimated from previous studies. The values of the targets regarding consumption of fuel wood and poles were based on a study by Nhantumbo and Soto (1994). However, these target values also take into account the demand for energy from the food processing industry (Pereira 1990).

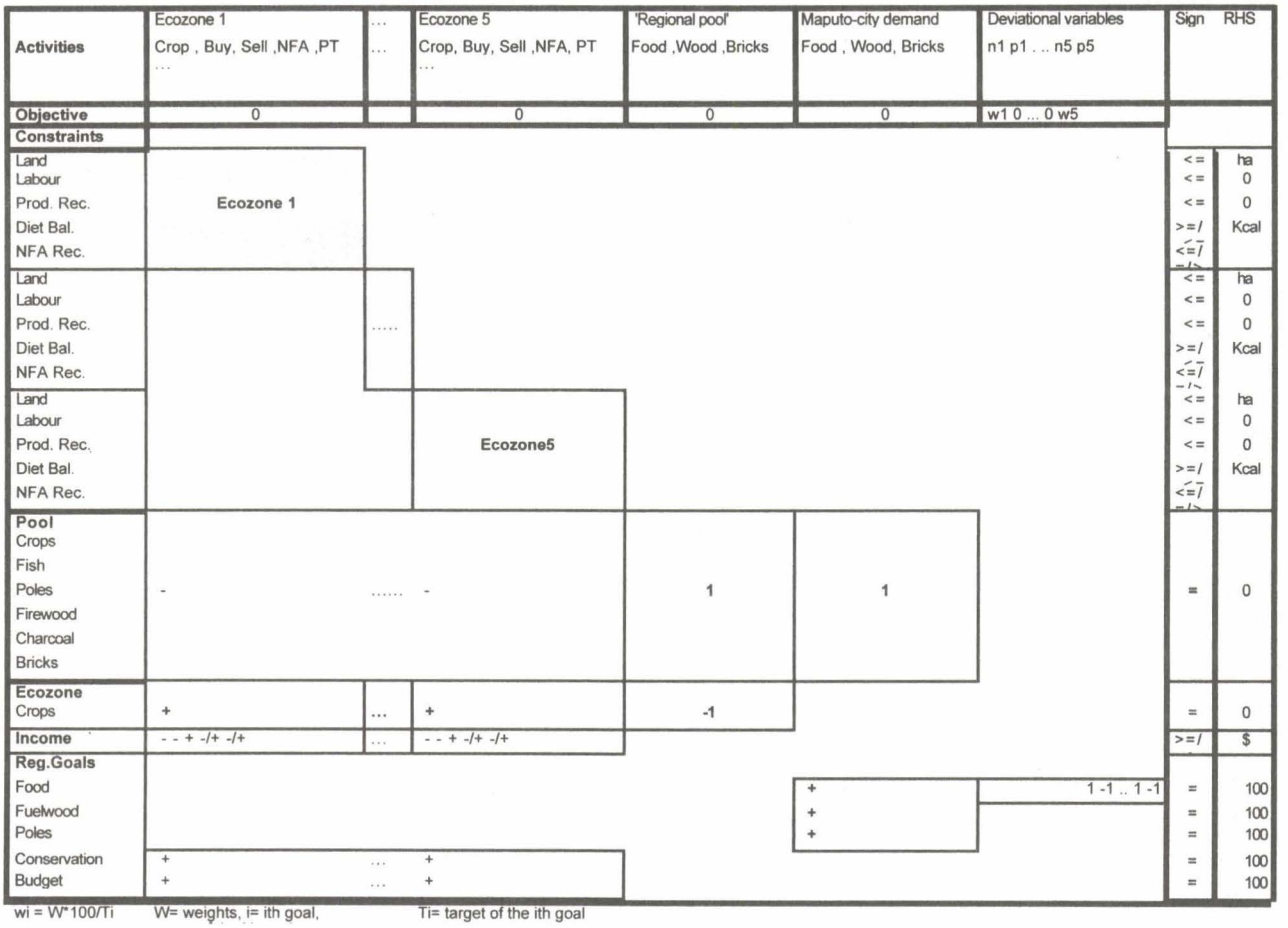

Figure 1.—*Structure of the regional model.*

The food target is based on population information (DNE 1994) and daily energy requirements, aggregated to reflect annual demand and consumption. Unlike the farm models, no dietary constraints were included in the regional model due to the complexities associated with the heterogeneity of the population in terms of their origin and dietary habits and disparity of income levels between urban and suburban dwellers in Maputo-city.

With regard to the conservation target, it was assumed that each household would plant at least 1 hectare of trees. The budget constraint reflects, in turn, the cost of planting that area with any of the tree species included in the farm model (*Leucaena* spp., *Eucalyptus* spp., *Melia* spp.).

Weights and Deviational Variables

As indicated above, there are various key decision-makers at the regional level. It therefore appears more appropriate to rank the several goals of the DM/PMs and derive weights which encapsulate not only their preferences, but also reflect the relative importance attached to the goals as well as the relative significance of positive or negative deviations (Cohon 1978).

The weights for each goal were determined using the procedure described by Yoon and Huang (1995) for derivation of weights from ranks. These were determined by the frequency at which each goal was placed at a certain rank by the various policy makers. Exchanges in the position of ranks allowed the evaluation of the trade-offs amongst the objectives according to associated weights (see results).

Weighted Goal Programming (WGP) simultaneously considers all goals in a composite objective function minimizing the deviations between goals and aspiration levels (Romero and Rehman 1989, Romero 1991). The objective function of a WGP model is meaningless when it aggregates incommensurable deviational variables (Romero 1991). Therefore, a normalization method which scales the deviational variables using relative percentages was used. Besides reducing significantly the

range of units which can affect results of models run in the simplex algorithm, it provides meaningful results because the objective function is a sum of percentages, which are adimensional, and the new sets of weights (w_i/ b_i) represent the preference of the DM.

RESULTS OF THE REGIONAL MODEL

The Scenarios

The regional model was run four times, each time changing the weights or the relative importance of goals as defined by planners or policy makers (table 2). This was done to assess how farm activities might change and thus how the regional situation might benefit from changing priorities.

These changes of preferences may be dictated by change in the economic situation resulting from political stability and better climatic conditions, change in policy makers, and hence their perception of the problems and priorities.

The Achievement Function

The representative farm models for each of the ecozones were run first as LP and Lexicographic Goal Programming (LGP) models in which the efficiency determined the maximum use of all resources available in the first case and, trade-offs between farm goals were provided in the second case. However, alternatives generated by the WGP aiming for the 'satisfaction' of the regional goals resulted in a large proportion of unused resources, such as labor and land.

Table 3 presents the achievement of the various goals, with the target multiples (the number of times the target is exceeded) given for each scenario. All multiples are positive since all goals were at least achieved.

In Run A when wood for energy supply to Maputo-city is the most important for the policy makers, then three of the four ecozones producing charcoal, produce at their full capacity. This results in more than twice as much fuel wood being produced over that required by the target. The result is validated by experience in the Maputo-city market where shortages of firewood are uncommon, despite difficulties of access to the production zones experienced by timber merchants in the wet season. Increased production and transportation costs generally reflect higher fuel wood prices, rather than less supply.

Only one ecozone currently produces poles from the natural forest. However, with tree plantations, the supply of volume required for building houses in the Maputo-city suburbs is substantially surpassed (P_2) in all runs. It should be stressed, however, in a similar fashion to fuel wood and food goals, wood demand for construction in the rural areas is endogenous to the representative farm model and the target of the region refers only to the Maputo-city consumer demand. The achievement of this goal is directly associated with the conservation goal which is also overachieved (P_4).

The Grassland ecozone has the highest area of land allocated to trees at 21 ha, 17 ha, 16 ha, and 27 ha, per household, respectively, in Run A, Run B, Run C, and Run D, and this is the main reason for such an excess over the target level. In all the other ecozones, the representative farm only plants 1 hectare. This result seems to correspond to the fact that the Grassland ecozone is the poorest ecozone in terms of agricultural performance and in terms of opportunities for income generation. Therefore, it is reasonable that the reforestation strategy offers an alternative both in terms of employment and income from wood sales. This also conforms with the reasoning that farmers in the most productive ecozones have no preference for planting large areas with trees, but would rather plant enough to hinder the expansion of the saline land, for instance. Conversely, the Thicket ecozone still has a significant natural tree cover and it would not be rational, in terms of sustainable use of the natural forest, to substitute it with a plantation of *Eucalyptus* spp., for instance. Therefore, a 1-hectare plantation, as shown by the model output, may not be a pessimistic target.

In the Dryland ecozone, the rationale for planting only 1 hectare of trees may be associated with the fact that farmers may be willing to expand their agricultural land in order to meet consumption requirements rather than transforming the ecozone into a forest area. The particular benefit that this ecozone can get is from the improvement of soil fertility through incorporation of leaf biomass if the selected tree specie was *Leucaena* spp. instead of *Eucalyptus* spp. Finally, in the Open Forest ecozone, the plantation of 1 hectare can be justified as protection of the crops from the reported damage of strong winds.

The food goal is expressed in terms of dietary energy (Kcal) and the solutions of all but one scenario (Run B) show an overachievement of this goal. In the first three scenarios such satisfaction is derived mainly from sweet potato and fish. However, Run D, appears more realistic due to a wider range of crops supplying a significant amount of maize and cassava which together with sweet potato and by-products form the major contributions to the diet of Maputo-city consumers from the ecozones.

It also is worth mentioning that diet constraints (fig. 1) have been included as endogenous constraints to each of

Table 2.—*Weights associated to the goals in each scenario*

Scenarios	Run A (survey)	Run B	Run C	Run D
Fuelwood	Highest	2nd Highest	2nd Highest	3rd Highest
Poles	Highest	2nd Highest	2nd Highest	3rd Highest
Food	2nd Highest	Highest	3rd Highest	Lowest
Conservation	3rd Highest	3rd Highest	Highest	2nd Highest
Budget	Lowest	Lowest	Lowest	Highest

Table 3.—*Target multiples resulting from change in priorities of PMS*

	Run A	Run B	Run C	Run D
P1 (Fuel wood)	2.17	1	1	1
P2 (Poles)	111.53	69.8	69.62	38.93
P3 (Food)	1.06	1	1.10	1.33
P4 (Conservation)	1.42	1.33	1.32	1.56
P5 (Budget)	1.33	1.24	1.23	1.49

the farm models. These may be interpreted as all ecozones satisfying the 'domestic' demand for food. Consequently, it may also suggest that in Maputo province everyone has access to food to meet at least the minimum energy requirement. Nevertheless, the purpose of including such constraints is to simply evaluate the level of food self-reliance of the farm. The interecozone trade serves to show the potential capacity of the ecozones generating surplus to supply the deficient ones.

Finally, it is obvious that planting more area than the conservation target stipulates will need more investment, hence the overachievement of the budget target.

Farmers Response in Terms of Land Use and Income

The change in the relative importance of the goals also results in a modification of farmers response in terms of land allocation to individual crops and the total area farmed by each typical farm. Although there is only a slight change (perhaps negligible) in the total farmed area particularly in the less productive areas (Dryland, Open forest, and Grassland), land allocation per crop changes significantly in all ecozones illustrated by the changes which occurred within the food goal as shown in table 2.

As regards income generation constraints, because the multiobjective regional model seeks a compromise solution then the income generated by the five representative farms only covers the minimum bound ($10,000). Despite that, it is important to retain this constraint because even though it was difficult to derive the income distribution envisaged by the policy makers, the reforestation strategy can only succeed if its implementation does not mean that farmers would have to forego too much in terms of food security, for instance, which can come from their own production or from purchases if cash is available.

DISCUSSION AND CONCLUSIONS

Clearly for such a planning tool to be successfully operational, validation of the farm-level component of the model becomes an issue. McCarl (1984) defines a model as an 'adequate' abstraction of reality for its anticipated use. Validation is a process of evaluation of the usefulness of such a model. Therefore, to comply with this basic requirement of modelling, the farm models which form the main building blocks of the regional model, were validated via expert opinion, an acceptable and widely used method (McCarl 1984, Hazel and Norton 1986). Furthermore, due to the difficulties of data availability and its reliability for construction of models for policy analysis in Mozambique, as in many developing countries, particular emphasis was given to the logic structure of the model. This, according to Hazel and Norton (1986), is better than compounding the data problems with poor logic. Therefore, subjective judgement of the output assuming a broad comprehension of the system represented by the model (Dent and Blackie 1979) was used under the concept that the

model should be judged relevant for its task (Beck *et al.* 1995). Consequently, having judged the basic structures to be valid, the link between the various parts of the model, the "regional pool" and the Maputo-city demand activities set the trade relations between ecozones and with Maputo-city market. Hence, it can reasonably be concluded that the regional model structure adequately represents the problem.

One important aspect that is also worth mentioning concerns the assumptions made to reduce aggregation bias. A basic assumption of the model implies that farmers within each ecozone have similar production possibilities and despite the relatively free access to land, traditional explicit and implicit rules create uniformity of land tenure conditions. This guarantees the proportionality of resource endowments, which according to Norton (1995), are probably the most relevant of Day's criteria for unbiased aggregation. Moreover, the survey data for this research and previous observations by Getahun (1991) and Bila (1992) showed that farmers are aware of environmental and fuel wood shortage problems created by deforestation and, similarly to the policy makers, see reforestation as the likely solution. Therefore, this reduces what Janssen (1995) considers a shift in the rationale (private and public) due to aggregation of farm to regional level.

In short, this model is a proposal for *ex ante* policy analysis regarding the potential impact of implementation of the participatory reforestation strategy in Maputo province and possibly in other provinces of Mozambique where the reforestation strategy has particular relevance. The model output delivers information regarding the opportunity cost resulting from shifts in the definition of the importance of goals and the resulting impact at a micro level. The final confidence in the model can only grow, as Beck *et al.* (1995) underlines, with its successful application. This, of course, implies operational validation or validation of the model as it is used (McCarl 1984). Nevertheless, the basis for planning and analyzing the potential impact of a reforestation strategy has been built and provides a framework for similar analyses in data scarce environments.

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THE ROLE OF AGRICULTURAL LANDS IN TIMBER AND BIOMASS PRODUCTION

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ABSTRACT. —The potential of certain agricultural lands to be converted to short-rotation poplar production in order to reduce harvest pressure on commercial forests was examined. An optimization model, a transportation model, and a poplar production model were utilized to generate optimal management schemes. The output is the marginal cost of delivered timber, location, and quantity of agricultural lands harvested in each planning period. The results show that agricultural lands can play a critical role in meeting timber and fuelwood demands over time. The role of agricultural lands as sole providers of fuelwood was also analyzed.

INTRODUCTION

Increases in market and non-market demands for natural resources are compelling decision-makers to rethink current natural resource management policies. The demand for forest products has grown substantially in recent years and is expected to continue to grow well into the next century. Public concerns over forest industry expansion and its perceived negative impacts on the environment stimulated preparation of a Generic Environmental Impact Statement (Jaako Pöyry 1992), which indicated potential constraints in meeting existing and future timber demands in the state. There is a particular shortage expected in aspen production due to the unequal age class distribution of currently growing timber.

Electricity is traditionally produced from non-renewable resources such as coal, natural gas, petroleum, or nuclear energy. Since energy production from these fuels can result in environmental externalities such as emissions of sulphur and carbon, there is an increasing public interest in the possibility of using substitute fuels such as biomass. The use of biomass energy for large-scale electricity production is not a new idea. It was thoroughly examined, for example, during the oil crisis of the mid-1970's. The idea was rejected because it was considered cost ineffective when compared to fossil fuels or nuclear energy. Now, 30 years later, biomass energy production is again gaining public attention. The present study examines the relationship of the forest and electric power industries by focusing on the use of wood as either a biomass fuel or as a traditional timber product.

Increasing demand for wood has resulted in higher timber prices in recent years. Wood-fired power plants would add to this demand and thus further increase timber prices. In order to meet these increased demands, it is being advocated that short-rotation woody crops (SRWCs) be produced on marginal agricultural lands such as those set aside under the Conservation Reserve Program (CRP). These lands, it is argued, have the potential to provide both fuelwood and timber, thereby reducing harvest pressures on traditional forest lands. This could also provide farmers with an additional cash crop assuming that markets will exist. Soil erosion and water contamination concerns might be reduced because of the relatively long rotation periods associated with SRWCs and reduced reliance on pesticides and herbicides which contribute to water contamination.

Production of SRWCs on agricultural lands might permit some landowners to diversify their crop operations. This is particularly relevant in light of the 1996 Farm Bill which incorporates several reforms and structural changes in the United States agricultural policy. In short, agricultural subsidies are to be phased out by 2003. Most of CRP acres will come out of contract by 1999, perhaps to be returned to annual crop production. In the absence of price support programs, this increased production might result in lower crop prices which can have substantial national and international consequences. Because some of the CRP acreage is highly erodible, its return to annual cropping could result in an increase in soil erosion and surface water contamination.

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Proponents argue that growing SRWCs on agricultural lands, particularly those that are adjacent to the current forest lands and not highly erodible as energy or fiber plantations might have a positive impact on the economy as well as on the environment. However, before energy production plants are built and large investments into farm-grown woody biomass are made, it must be understood how such developments would fit with the existing economic and environmental conditions.

OBJECTIVES

In this research, we examine the role of marginal agricultural lands in Minnesota as potential fuelwood and timber suppliers. We assume that hybrid poplar produced on these lands can either be used as a substitute for timber or as fuelwood. Although we considered traditional forest lands as well as agricultural lands, the focus of this paper is on the role of agricultural lands only. Expected future aspen demands at six aggregated forest markets and biomass requirements for two 100MW power plants are modeled.

A set of spatial and dynamic optimization models (DTRAN, GISTRAN) is used to estimate the delivered timber and fuelwood prices under different cost and production assumptions over ten 10-year planning periods (Hoganson and Rose 1984, Kapple and Hoganson 1991, Husain 1997). The combination of forest lands as well as agricultural lands in a location specific environment adds a new dimension to the previous planning efforts. Furthermore, the inclusion of transportation cost based on actual road distances between analysis areas and the market locations provides better estimates of delivered costs. The results of this study show the amount and location of agricultural lands best suited for poplar production under several management scenarios.

STUDY DATA

The forest markets considered in this study are Brainerd, Bemidji, Cook, Duluth, Grand Rapids, and International Falls. These locations represent the major concentration of forest industries in Minnesota. The power plant locations considered are Alexandria and Granite Falls. These locations were specifically chosen because they appear to meet the potential requirements for the establishment of biomass operated power plants, as spelled out by EPRI (1994) and are currently under consideration.

Agricultural Land Attributes

The farm land data set for this study was obtained from the Minnesota Department of Agriculture (MDA). This tabular database was created by each county's Farm Services Agency (FSA) office by running a standard query on county CRP records in September of 1994. According to FSA's summary statistics, there were 1,834,411 acres enrolled in Minnesota before the implementation of the "Early Release Program" in 1995. The key attributes of the database included the legal description of the location of each land parcel, acreage, rent rate, current conservation practice, indication whether the land parcel is highly erodible or is a wetland, and the land capability class (LCC), and land capability sub-class (LCSC) as defined by the Natural Resource Conservation Service (NRCS).

State-wide totals for acreage in major land categories such as highly erodible lands and their distribution in wetlands and converted wetlands are presented in table 1. The acreage reported as highly erodible (830,000 acres) was excluded from further analysis. Steep slopes or other severe soil limitations associated with these lands render them unsuitable for any type of farming activity, including tree growth. Those lands classified as unknown (90,000 acres) were not excluded from the analysis, except for wetlands. Wetlands are said to provide several environmental and economic benefits and their destruction can have significant long-term impact on the ecosystem itself. Therefore, acreage consisting of confirmed non-converted wetlands (420,000 and 22,000) was also excluded.

These exclusions left the agricultural land database with 438,364 acres, about 26 percent of the original database. This portion of the agricultural land data was modeled in this study for possible planting to hybrid poplar.

Location of Agricultural Lands

The UTM coordinate system was used to represent the location of the aggregated land parcels within a township. Each parcel was treated as if it was located at the geographic center of the township. These coordinates provided the linkage between the land parcels and the transportation network used in this analysis. UTMs were calculated using software known as SECTIC-24K, developed by the Minnesota Land Management Information Center (LMIC).

HYBRID POPLAR

For this study, agricultural landowners are modeled as if they face a choice: (1) do not grow trees and rent the land or (2) grow hybrid poplar and sell it to potential power plants and/or to forest markets. Since hybrid poplar and aspen have similar product characteristics, it is assumed that they can be substituted for each other in all markets. In compliance with existing practices, an 8 X 8 spacing and an optimal rotation age of 10 years is assumed.

Table 1. —*Major agricultural land categories and their distribution (acres)*

Highly erodible lands (YES) 829,788 acres			
Attributes/Indicator	Yes	No	Unknown
Wetlands indicated	468,289	265,054	96,445
Wetlands converted	6,720		
Highly erodible lands (NO) 786,095 acres			
Attributes/Indicator	Yes	No	Unknown
Wetlands indicated	419,800	286,173*	80,122*
Wetlands converted	2,157*		
Highly erodible lands (UNKNOWN) 89,558 acres			
Attributes/Indicator	Yes	No	Unknown
Wetlands indicated	21,765	8,383*	59,410*
Wetlands converted	2,119*		

Notes: * indicates agricultural lands included in the analysis.

Ongoing research on intensively managed plantations provides some reliable information on the production potential of short-rotation hybrid poplar clones. In Minnesota, yield rates are expected to range between 2 to 5 dry tons/acre/year, according to soil and climatic conditions. These estimates are mostly derived from a network of research plantations which were established in a five-state region of the north central U.S. during the 1980s (Hansen *et al.* 1994). In the present study, yield rates are modeled as a function of NRCS land capability classes and subclasses, rainfall, and soil types. In general, soils with a higher productivity rating for agricultural crops will also be more suitable for hybrid poplar. However, this link is not expected to hold for soils with poor drainage conditions, because hybrid poplar tends to grow well under such conditions (Berguson 1994).

Production Costs

Estimates of variable production costs for hybrid poplar production were obtained from the Natural Resources Research Institute (NRRI), based on actual cost data associated with a network of plantations in Minnesota and Wisconsin. In general, most expenses incurred in the production of hybrid poplar occur during the establishment phase. After successful establishment usually there are no other significant costs until harvest. The only exception might be in case of disease, which may result in additional costs, but these are not modeled in this study. In addition to the traditional production costs, CRP land rents associated with each land parcel are used as the opportunity cost of the landowner participation.

Harvest and Transportation Costs

Harvest and transportation costs are extremely significant components of the timber production process. In general, transportation costs are approximately one-third of the total costs associated with the procurement of timber. In some cases, these costs can actually be higher than the stumpage value of a given stand. Despite this, transportation costs are often not considered in the timber management and modeling studies.

Two separate estimates of harvest costs for hybrid poplar were generated. One reflects the traditional harvesting technology, and the other represents the whole tree harvesting systems which avoid expensive operations such as wood chipping and partial skidding. In Minnesota, data on hybrid poplar harvesting costs are rare because most of the large scale plantations are still below harvesting age. Therefore, this study utilized harvesting cost estimates generated by the Oak Ridge National Laboratories (ORNL) for the Great Lakes region (Walsh 1994). Appropriate adjustments were made to reflect the regional conditions and specific assumptions of this research. The adjusted harvest costs for hybrid poplar in Minnesota given (1) Conventional Harvest are $450 per acre with an additional loading and processing cost of 4.75 per dry ton. (2) Whole Tree Harvest is $270 per acre with an additional loading and processing cost of 4.75 per dry ton. In addition to these charges, a 0.15 cent per dry ton per mile charge was also applied to cover hauling costs. The model is further calibrated so that hybrid poplar sold as pulpwood in the forest markets will be harvested conventionally because these markets generally require additional on-site processing. Hybrid poplar sold to power plants will be harvested and processed with the whole tree harvesting technology.

RESULTS

The results for fuelwood demands using only agricultural lands for Alexandria and Granite Falls are presented in table 2. These results are based on the assumption that whole trees are delivered to the power plants and that farmers use CRP rent rates as their opportunity cost of participation. Approximately 95-100 thousand acres of

Table 2. —*Final results for all independent fuelwood supply scenarios*

Scenario	Acres	Dry tons	Total cost ($)	Average ($/dt)	Minimum ($/dt)	Maximum ($/dt)	Average ($/MBtu)
1[A]	94,546	3,501,769	112,071,938	31.86	20.73	35.68	1.85
2[B]	98,809	3,502,947	127,014,242	36.25	23.56	39.99	2.11

Notes: [A] indicates Alexandria power plant with unchipped wood and CRP payment rates.
[B] indicates Granite Falls power plant with unchipped wood and CRP payment rates.

land capable of producing about 3.5 million dry tons of wood are required to fuel each power plant for each 10 year planning period (350,000 dt/year). Table 2 also shows the maximum and the minimum costs per dry ton. The maximum cost can be interpreted as the marginal cost of delivered fuelwood because it is the cost associated with the last unit of fuelwood delivered to a given power plant. The minimum costs are simply the cost of fuelwood delivered from a location with the lowest overall cost.

The delivered fuelwood costs at Alexandria are on average about $5/dt lower than Granite Falls. This is simply because those agricultural lands closer to Granite Falls generally fall into the category of good agricultural lands with relatively higher opportunity costs. These high land rents translate into higher production costs, which make it more cost effective to transport fuelwood from lands that are further away but have lower rents. The yields on lands closer to Granite Falls are not so high that they can off-set their higher opportunity costs. The average distance between production sites and Alexandria is approximately 60 miles.

The weighted average delivered fuelwood costs for all townships supplying to Alexandria were also calculated. The cost estimates associated with each yield rate in a given township were weighted by the number of acres to determine the total average costs for a given township. In most townships, delivered costs ranged between $28/dt and $36/dt ($1.98/MBtu). Townships in the west and north-central part of the state deliver the majority of the fuelwood. No fuelwood is supplied from the southern part of the state primarily because of the higher land rents in that area. The range of fuelwood traveling distance is between 4 and 188 miles, with an average distance of 62 miles.

The weighted delivered fuelwood costs for the majority of townships supplying to Granite Falls are between $31/dt and $40/dt and a few townships have costs within $25/dt and $31/dt. Again, higher land opportunity costs result in most of the fuelwood being shipped from the central and west-central part of the State, in spite of the fact that other agricultural lands are closer to Granite Falls. The transportation distances vary by as much as 7 to 211 miles, with an average distance of 91 miles.

While the aspen demand for the initial 4-5 decades cannot be met using only forest lands, the introduction of hybrid poplar produced on agricultural lands changes the results substantially. Since there is little difference between the physical and chemical properties of aspen and hybrid poplar, they can be modeled as if their markets were identical. The inclusion of agricultural lands substantially reduces aspen shadow prices and the demand targets for all markets and planning periods are satisfied. Shadow prices generally rise for the first four periods before they begin to steadily decline, but their patterns are not uniform across markets.

Those markets that bought wood from agricultural land generally exhibit the lowest shadow prices. As a rule, these markets are located closer to agricultural lands with low opportunity costs and high yield rates.

Figure 1 shows the acreage of agricultural lands utilized to meet aspen demands for all planning periods and markets. No agricultural land is harvested in the first planning period because the rotation for hybrid poplar is 10 years and therefore it will not be available for harvest until the beginning of the second planning period. The lowest shadow prices are associated with Bemidji, primarily because it is located closer to large acreages of agricultural lands with relatively low opportunity costs. About 70-80 thousand acres of these lands are used to meet the demands at the Bemidji market in each planning period. The highest shadow prices are associated with Duluth and Grand Rapids markets, which receive most of their aspen supply from commercial forest lands. The wood from agricultural lands allocated to Duluth and Grand Rapids markets is relatively insignificant. The only market that does not receive any supply from these lands is Cook. This market is located in the north-eastern part of the State. There are very few agricultural lands near this market and therefore, all its aspen requirements are met by the commercial aspen stands located nearby.

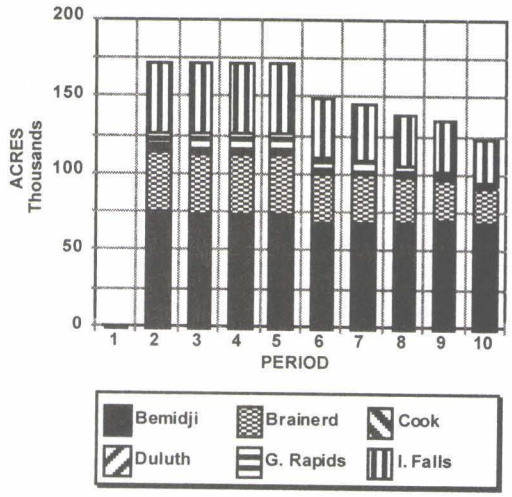

Figure 1. —*Agricultural lands harvested (acres).*

It is interesting to note that after the first four periods the harvested acreage of agricultural lands starts to decline, reflecting the fact that the age class imbalance of aspen stands will begin to improve in about 40 years. Therefore, its ability to provide industrial quality aspen becomes more stable. Because hybrid poplar produced on agricultural lands is generally more expensive than aspen produced on forest lands, the model always picks aspen stands over poplar provided that aspen is physically available. This is the main reason for the reduction in agricultural acres harvested during the later planning periods.

The acreage of agricultural lands harvested to meet fuelwood requirements was not substantial when forest lands were also available for harvest. The main reason for this is that relatively abundant stands of northern hardwoods with relatively higher Btu content than hybrid poplar are available for harvest and therefore, it is economical to supply northern hardwood to the power plants. Furthermore, since there is a shortage of aspen, the model allocates most of the poplar produced on agricultural lands to the traditional forest markets, not to the power plants. Figure 2 illustrates that for both power plants only 8 thousand acres were allocated in the initial planning periods and approximately 11 thousand acres in the later planning period. This increase in acreage harvested during the later periods reflects the restricted supply of hardwoods from the forest lands. Most of the fuelwood produced on these lands goes to Granite Falls because it is relatively distant from the forest lands and closer to the agricultural lands. About 8 thousand acres are harvested in each planning period for Granite Falls. In comparison, the allocation of agricultural lands to Alexandria is insignificant at least in the first five planning periods. But as the fuelwood supply from the forest lands begins to tighten, the acreage of these lands increases to a little over 3 thousand acres in the remaining planning periods.

CONCLUSION

Modeling timber and fuelwood supply from traditional forest lands and agricultural lands managed under short-rotation production alternatives adds a new dimension to

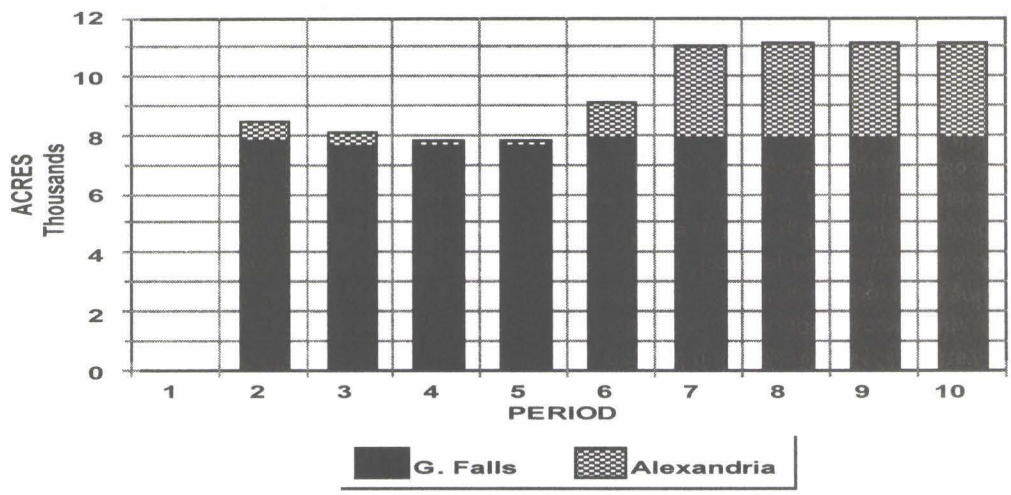

Figure 2. —*Agricultural lands harvested for fuelwood when forest lands were available (acres).*

previous Minnesota forest planning efforts. The present study's use of location specific information and realistic estimates of production, harvesting, and transportation costs can provide decision makers with reliable estimates of marginal costs for delivered timber and biomass products.

This research assumed that whenever necessary, the forest industry can use short-rotation hybrid poplar produced on agricultural lands as a substitute for aspen. The results indicate that the inclusion of these lands allows the aspen demands at all markets to be satisfied over all planning periods.

The use of agricultural lands particularly in the initial planning periods has a significant impact on aspen prices and the acreage of forest lands harvested. Production of hybrid poplar results in large quantities of wood in a relatively short time and thus significantly reduces the harvest of traditional forest lands. At most, about 200 thousand acres of these lands provide hybrid poplar to the timber markets in each planning period. It should be noted that not every township with agricultural acreage is allocated to timber production. The combination of landowner opportunity cost, the transportation costs to timber demand markets, and the soil productivity influence the economics of timber production and determine the relative advantage of one township versus another.

Estimates of fuelwood costs were also computed under the assumption that forest lands will also be able to provide fuelwood. The role of agricultural lands significantly decreased in this case because of the apparent differences in the energy contents of hybrid poplar and other forest species such as northern hardwoods. The fuelwood marginal costs rise in each subsequent planning period indicating that fuelwood supply from forest lands becomes constrained over the planning horizon. The role of agricultural lands as fuelwood supplier becomes relatively significant in these later planning periods, particularly for Alexandria.

Since it turns out that the power plants modeled in this study would most cost effectively acquire fuelwood from existing forest lands, substantial savings could be achieved if the plants are located in the northern part of the State where major concentrations of the forest lands exist, rather than the currently proposed southwestern locations.

The results of this study also indicate that poplar produced on agricultural lands has a better chance of being used in the forest industry than in the power plants. This is because forest markets can pay more for poplar than the power plants. In comparison, the power plants can use northern hardwoods, which are available at relatively lower costs and have a higher energy content.

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INTEGRATING THE BIODIVERSITY MANAGEMENT AREA SELECTION MODEL INTO A MULTI-USE FOREST PROGRAMMING MODEL: THE CASE OF RELMDSS

Richard L. Church, William J. Okin, Michael Figueroa, and Klaus Barber[1]

ABSTRACT.—Forest management has evolved from a multiuse perspective to include both natural resource and ecosystem management. Ecosystem management involves the protection and enhancement of natural environments with the long-term objective of ensuring biodiversity. This paper describes a model that has been developed to help select areas in a forested region that should be managed to enhance the long-term level of biodiversity. Such a model can be integrated with a multi-use forest planning model within a spatial decision support system to provide forest planners and analysts the capability of determining the tradeoffs between biodiversity management goals and traditional forest management objectives.

INTRODUCTION

For many governmental agencies in the United States including the USDI Bureau of Land Management and the USDA Forest Service, forest management over the past 50 years has evolved from a simple, single objective timber resource problem to a more complex multi-use management problem. With the recognition that some species are at risk of extinction, the Endangered Species Act further changed the character of forest management. In addition, the National Environmental Protection Act (NEPA) made it mandatory that environmental impacts be assessed in major governmental operations. Consequently, the problems of forest management have become increasingly more complex and difficult to assess. It is easy to see that in many regions of the Forest Service, much of the time and effort spent in determining management options involves environmental impact assessment, mitigation, and analysis. The largest and most costly study performed in Region 5 of the Forest Service in recent history involved two independent studies of the Sierra Nevada region within the context of the long term survival of the spotted owl and other threatened or endangered species. In the Pacific Northwest, considerable time and effort has been spent in addressing forest operations and the impact on such species as the spotted owl and steelhead trout.

Addressing major environmental impacts on a regional basis has changed the character of institutional approaches for analysis. For example in the Pacific Northwest, the now famous study on the spotted owl was developed by a team of scientists and forest analysts who were brought together from a variety of positions and areas—university, forest planners, and forest researchers. Such regional studies cut across a number of National Forests as well as other governmental managed land units like the Bureau of Land Management. Dippon (1997) presents an example of cooperative forest management planning involving the BLM and the Forest Service where both agencies are managing land in the same watershed. Such cooperative and regional studies will become more common as the distribution and habitat of threatened species must not be analyzed forest by forest but on a larger regional scale.

At issue is the need to identify those lands that can be effectively used to ensure the continued presence of species that are either threatened or have been dwindling in numbers. Management alternatives for such critical areas might involve wilderness protection, the elimination of grazing, reduced forest operations or a combination of one or more management actions. In some areas, increased activities may help in long term viability. Such activities clearly fit within a context of operating to meet or exceed a desired future condition. The objective of this paper is to present a model which was developed as a part of the Sierra Nevada Ecosystem Project (SNEP). This model is called the Biodiversity Management Area

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Selection model (BMAS). It can be used to identify the most effective areas for maintaining a minimum range or distribution of species or biological elements that are threatened. The basic premise is that it is important to identify those land units that can be effective in planning for and maintaining biodiversity as a part of overall forest management. Given that such areas are identified, then it is necessary to integrate this need and the potential into overall forest planning. Such an analysis may be performed at the regional scale, or at the forest scale given targets that have been defined for the region and dissaggregated for the individual forest. The remainder of this paper describes the BMAS model and the present plan to integrate the model into the Regional Ecosystem and Land Management Decision Support System (RELMdss).

OVERVIEW OF THE BMAS STRATEGY

There have been several approaches that have been developed for identifying land units which should be reserved for the purpose of biodiversity protection. Such approaches fall into principally two categories: (1) reserve design and (2) site selection. Reserve design models involve the selection of land parcels which, in total, yield a contiguous area of land which has (1) a large enough size that it maintains a viable habitat for one or more species, (2) it is as compact as possible and involves a low perimeter to area ratio, (3) includes sufficient habitat of a suitable quality for the species of interest. Reserve site selection involves the selection of independent parcels which together, combine a sufficient level of land and biota protection that: (1) represents as many species as possible, (2) represents those species which are considered endangered. It is assumed that sites are of viable sizes. The units are usually selected independent of arrangement. Often reserve design models are meant to delineate the best site crafted from a set of prospective parcels whereas reserve site selection models involve selecting from a wide variety of sites—a collection of sites which together meets a number of regional targets for representativeness and distribution.

As the landscape of natural areas becomes more fragmented by land use conversion from natural to agricultural, urban, recreation, or other, the viability of certain species may be threatened. Unfortunately, the exact habitat response and potential for viability is not well understood for most species. Just what is required for the long run viability of a given plant or animal is often not known. Even though we might not know exactly what is needed for a given species, there are two ways that we can approach this problem with some certainty that protection will be afforded. First, threatened species do need to be represented in reserve areas. Second, the more area that involves a given species, the better. Third, connectedness is usually good, involving wider pools of genetic diversity for a given range of animals and plants. Third, it is important to concentrate scientific efforts on understanding those sentinel species which can be used as indicators of overall heath and viability.

The approach taken in the development of the BMAS model involves the first two types of objectives. First, areas selected for enhanced biodiversity management or protection should represent those species which are threatened or where the amount of viable habitat is decreasing. Second, the BMAS model involves selecting at least a minimum amount of habitat or species range for a given threatened species or element. Since a large region of the Sierra Nevada is managed for renewable resources like grazing, timber harvesting, and recreation including hunting and fishing, much of the region falls outside of the category of intense land use. Consequently, it seems reasonable that connectedness is in part provided by the fact that selected biodiversity management areas will fall within a matrix of large government and private tracts of land managed for renewable resources. The threat to habitat destruction and fragmentation and their impact on species viability is based in part on land-use conversion to more intense activities, like residential subdivisions or by activities like increased road building, etc., and incompatible land uses like grazing in a sensitive riparian zone. The idea is that because many areas of the Sierra Nevada are managed as a part of a large renewable resource industry, areas selected for biodiversity can act as protected or managed areas that insure the presence of species across the Sierras. Areas managed for natural resources may not necessarily preclude such viability in and of itself. Such BMA areas would serve as the source of and species viability at a level of higher protection or management. Thus, a Sierra BMA system would not function as an archipelago of biological reserves, but as a "core area" of higher quality for many species and/or sanctuaries for species and habitat types that are negatively impacted by human activities.

The basic strategy involved by the BMAS model is to select panning units for more intense management with the purpose of promoting biodiversity protection. This is accomplished by first identifying those species or habitats that are threatened and then determining the needed area to represent such species with at least a minimum level of protection. Then, the most efficient set of areas is selected which are needed to provide at least the minimum level of area distribution for each threatened species. The final step is accomplished by the solution of the BMAS model.

A MODEL FOR SELECTING BIODIVERSITY MANAGEMENT AREAS

The major objective is to represent the distribution of species or biodiversity elements which are at risk in a

core of biodiversity management areas to help provide for long term viability. Each biodiversity management area would be managed to enhance such elements that are considered at risk or are threatened. Management might mean simple prescriptions like eliminating grazing from riparian areas to substantial intervention in order to protect a special habitat. The major issue is to represent so called elements at risk by selecting enough management units that contain such elements that the total area of each element within the selected units meets some desired minimum standard. In order to apply a BMAS approach, it is necessary to have a database that reflects current land cover, habitat distribution, and species presence. Further, it is desirable to characterize as fully as possible human activities, especially roads, land-use zoning, population, industry, employment, etc. With such data, it is possible to forecast both land use and activities for a region. The ultimate objective of such a forecast would be to estimate land use changes. Such changes in land use can be used to identify the reduction in habitats that support various species. Thus, we can determine the extent to which various species, communities, endemic plants, old growth stands, etc. are at risk now or in the future. Any plant, animal, habitat, or community at risk will be called an element. We can think of elements at risk as being vulnerable as long as forecasted change is allowed to occur without some type of intervention or protection.

In order to apply the BMAS model it is necessary to define a basic decisionmaking unit. Such a unit should be land based: large enough to make sense, but small enough that flexibility is afforded. For the application of the BMAS model in the Sierra Nevada region, the land units were the watersheds defined by the California Department of Forestry and Fire Protection. For the Sierra Nevada range there are approximately 2,700 watersheds. The average watershed size is about 3,000 ha (or 7,000 ac.). Watersheds make logical planning units for they are easily located on the ground, are appropriate physiographic units for managing ecosystem and hydrologic processes, and may be large enough to support viable populations of many plant and animal species. The areal extent of every plant community type was calculated by intersecting the watershed boundaries with a map of plant community types (Davis *et al.* 1996). The vegetation map was prepared at a 1:100,000 scale for the gap analysis study of the Sierra Nevada. On the average, there are several plant community types for each watershed. Data was also collected on land use, population, roads, etc. for each watershed.

By forecasting land use conversion and increased activities, the loss of habitat for each species was calculated. Given such losses, species and communities were identified as being threatened. In order to protect an element at risk, it was determined that a certain fraction of existing distribution should be protected or maintained. If forecasted land-use changes meant that an element would no longer be represented at least at the minimum fraction of existing distribution, then that element was defined to be at risk. The area needed to raise the element from being at risk was defined as that amount of area that would be necessary to ensure that the existing habitat area was greater than the desired minimum fraction. Therefore, from forecasted land use and maps of existing vegetation and species distribution, it was determined which elements were at risk and how much protected area was necessary to keep the element from being at risk. We recognize that the minimum fraction used in the study was somewhat arbitrary (15 and 25 percent), and it is necessary to determine appropriate minimum fractions for each element.

BMAS Model and Notation

The BMAS model involves the selection of land units that can help provide needed core habitat among a matrix of land being managed for renewable resources. It has been expressively developed for those cases where there is significant land being devoted to primary industries such as timber harvesting and grazing. The model helps select those areas that would be most useful in maintaining a minimum distribution of specific elements that are determined to be at risk. In order to define the BMAS model mathematically, we need to introduce the following notation:

k,K = index and set of elements at risk,

j,J = index and set of planning units,

Min_k = minimum area containing element k that is needed under BMA distinction,

Hd_j = human density of planning unit j,

PPI_j = the density of public-private land interface in unit j,

Pla_j = percentage of area in private ownership for unit j,

a_j = the are of planning unit j,

r_j = percentage of the area in planning unit j which is impacted by roads,

a_{jk} = area of planning unit j which contains element k,

w_l = weight attached to term l in the objective,

X_j = $\begin{cases} 1, \text{ if watershed unit } j \text{ is selected for a BMA} \\ 0, \text{ if not} \end{cases}$

The BMAS model can now be formulated as:

$$Minimize\ Z = \sum_j (w_1 a_j + w_2 Hd_j + w_3 r_j + w_4 Pla_j + w_5 PPI_j) X_j$$

Subject to:

1) Ensure that element k is no longer in jeopardy

$$\sum_j a_{jk} X_j \geq Min_k \text{ for each } k \in K$$

2) Integer requirements

$$X_j = 0,1 \text{ for each } j \in J$$

The above formulation is deceptively simple. Each of the constraints represents a lower bound on what must be included among the chosen watersheds in terms of a given element. The objective minimizes a combination of a number of factors, each assigned a penalty weight. The first term is associated with minimizing the area of all chosen watersheds. The smaller the total area chosen for biodiversity management, the lower overall costs will be, including monitoring. The second term minimizes the choice of watersheds with high population. Thus, watersheds with lower population densities will be preferred. The third term discourages the choice of watersheds with a high level of road density. Road density represents the length of all roads divided by the total area of the watershed. The larger road density is, the more likely is the level of access and potential fragmentation. Thus, this third term encourages the choices towards areas that are less accessible and potentially less fragmented. The fourth term of the objective discourages the choice of watersheds that have a larger percentage of private ownership. The basic premise for this objective term is that the greater the level of public ownership in a given watershed, the easier it will be to declare and manage an area with biodiversity management being the primary objective. The fifth term of the objective discourages watersheds from being chosen that have a large level of public-land private-land interface. The greater the amount of interface between public and privately owned lands the higher the level of fragmentation and the greater the level of private ownership. The greater such levels are, the less likely such an area is either natural or easy to manage for biodiversity enhancement. In total, the objective tends to encourage the selection whenever possible of those watersheds that are publicly owned, have few people, and are less developed in terms of roads. For application solely with a national forest or a group of forests, planning units may involve land that lies solely within the national forest or potentially other areas as well. This would depend on the application. For the Sierra Nevada study, all watersheds were considered. For some areas it may be possible to demonstrate that certain biodiversity elements cannot be protected at all on public lands.

Even though the model is quite simple in structure, the BMAS formulation given above can be quite difficult to solve. This is due to the integer restrictions on the decision variables, where a watershed is either chosen or it isn't. In fact the formulation cannot be classified as integer friendly. However, techniques have been developed to tighten this formulation and make it easier to solve using linear programming with branch and bound (Church *et al.* 1997b). Heuristics have also been developed to solve the BMAS problem and have proven to be effective at solving relatively large BMAS problems. This is a subject of a recent research paper (Okin 1997). Results of the BMAS applied to the Sierra Nevada region are presented in the second volume of the SNEP report to Congress (Davis *et al.* 1996).

INTEGRATING THE BMAS MODEL INTO RELMDSS

One of the major elements missing from existing forest modeling systems such as SPECTRUM is a clearly defined methodology for handling issues of biodiversity protection and enhancement along with the more typical multiuse goals. Although it is possible to establish a target or goal for lands to be designated as a biodiversity option, it is not an entirely simple task given that it requires a discrete choice variable (i.e., integer variable). This is a factor that complicates the coordinated allocation of choices style of model originally developed in FORPLAN. Unfortunately, models like BMAS are not easy to solve and can easily tax a general purpose linear programming/integer programming software system. Special heuristics are necessary in many instances, and thus a system which allows for solution methodologies other than general purpose LP/IP is needed. It is desirable to integrate models like BMAS into strategic and tactical level planning models so that forest analysts can easily address the goals of ecosystem management. It is important to be able to solve for the tradeoff between desired levels of protection and harvesting. It is also necessary to track the potential impacts on dwindling habitats as strategic and tactical decisions are being made.

As a first step toward integrating the BMAS model into strategic and tactical level forest planning models, we have chosen to integrate the BMAS model into the RELMdss. The RELMdss model is a decision support system that is designed to be applied at both the tactical and strategic levels (Church *et al.* 1997a). Its development has been supported by the Forest Service in order to track and resolve constraints involving standards and

guideline conditions at a higher level of spatial resolution than typically used in such models as SPECTRUM. It also contains a user interface which allows the analyst to visually inspect flexibility across planning units. Unfortunately, the structure of the BMAS model does not easily fit within the five models currently defined in RELMdss. In order to integrate the BMAS model into RELMdss, it is necessary to first expand the definition of one of the main RELM models so that both data input and model structure can encompass the BMAS problem as well. Such a model and data input expansion is currently under development. In addition, both integer programming and heuristic techniques will be needed in order to provide the capabilities to solve such a model over a range of sizes. The development plan is to add the capability to RELMdss so that a series of models can be solved sequentially on the same area, where the results of one model are fed into the next model. As an example, let's assume that we first solve a BMAS model in order to identify a set of planning units to set aside for biodiversity management. Such a designation would not necessarily preclude all harvesting activities, but it may mean additional limits on thresholds established for specific standards and guidelines (in order to classify the area as BMA). Then, such changes or BMA designations are made or fixed into the RELM model data. The analyst could follow the BMAS analysis by the solution of a classical RELMdss model like the MIN_AREA model. This model can be used to translate harvest targets and other activities to planning units in a manner which is then compatible with the BMA designations. Thus, biodiversity management goals can be directly integrated into the strategic or tactical level model. This allows the analyst to determine a plan which best fits the BMAS solution. The interface for the RELMdss will also be expanded in order to allow the analyst to easily change BMA designations and then resolve a model. The system will allow the analyst to reselect BMA units (designate a new BMA, eliminate an existing BMA designated unit, and track BMA element protection targets). Subsequent solution of the MIN_AREA model would then allow the analyst to check the impact of the new designations on the overall performance of the targets and goals. By giving the analyst to quickly change area designations, various spatial options can be explored and tradeoffs between levels of harvesting and BMA protection can be explored. Thus, we propose to integrate the Biodiversity planning elements with the more common multiuse management components in order to provide a flexible decision support system that can aid in ecosystem management.

SUMMARY

The purpose of the paper has been to present some of the details of the Biodiversity Management Area Selection model (BMAS). This model has been developed to help identify potential areas within a forested region that could be used to enhance or protect biodiversity. In order to solve for both biodiversity goals and more traditional multiuse goals, a flexible modeling approach is outlined which involves the BMAS model and the decision support system called RELMdss. Changes are underway to support the solution of BMAS model within the RELMdss system along with the capability of solving sequentially several models, both BMAS and RELMdss models. This will allow the analyst to feed results from one model as inputs into another model. This approach will make it possible for the analyst to easily explore possible options and tradeoffs between biodiversity management goals and more traditional multiuse goals.

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INTEGRATING GIS TECHNOLOGY WITH FOREST MANAGEMENT AND HABITAT ASSESSMENT EFFORTS ON OUR NATIONAL FORESTS

Joan M. Nichols, S. Arif Husain, and Christos Papadas[1]

ABSTRACT.—Research was conducted on a section of the Superior National Forest to develop and examine potential methods or approaches that may be used to integrate non-timber resources in multiple-use planning. An indicator species for old-growth conifer forests, pine marten (Martes americana), was chosen to examine potential conflicts between specific forest management practices and habitat values. This research explored an approach to combine spatially scheduled timber production and the impacts on marten habitat for a large area, examining simple management scenarios in the form of delayed harvesting. The results of the analysis indicate that clearcutting over the 50-year planning horizon had a significant impact on the marten habitat conditions of the study area only in specific management simulations.

INTRODUCTION

Within the past decade there has been growing awareness of the potentials as well as the importance of a quantitative understanding of natural resources, ecosystems, and the environment at various scales. Geographic Information Systems (GIS), with their capabilities for spatial analysis and modeling of diverse data sets, enhance the ability to address several natural resource and environmental issues that have a spatial component: e.g., biodiversity, land use planning, and wildlife habitat management. GIS facilitates the organization, manipulation and analysis of the myriad spatial and aspatial data often associated with these issues, and its data structures, and analytical techniques are being incorporated into a wide range of management and decisionmaking operations that pertain specifically to natural resources (Nichols *et al.* 1997).

Today, Geographic Information Systems (GIS) is thought of as an enabling technology for science because of the breadth of potential uses it has as a research tool. Developed and applied correctly, a GIS can provide forest resource managers with powerful information that will aid them in the development of management and planning decisions. Interfaced with predictive models, GIS technology can be extremely useful in resolving conflicts by presenting accurate data and alternatives as well as providing a potential user with the means to analyze and compare management alternatives.

Planning models that deal with integrated resource management concerns on national forests are now available to deal with vital spatial information. Advancements in GIS technology and natural resource modeling have made it possible to quantify various attributes so that a systematic examination and evaluation can be conducted for a given area. Use of a GIS can generate a level of spatial analysis that reflects the complex relationships represented within a given model and then incorporate these evaluations in the decision-making process. (Nichols *et al.* 1997).

STUDY AREA

Located in northern Minnesota, the 490 km^2 study area represents 4 percent of the 12,140 km^2 Superior National Forest, encompassing portions of the Tofte and Kawishiwi Ranger Districts. The landscape is covered with nearly continuous forest interspersed with wetlands. The forest vegetation includes both boreal and temperate components. The dominant upland coniferous tree species include black spruce, white pine, red pine, jack pine, white spruce, and balsam fir. The upland deciduous tree species include quaking aspen, bigtooth aspen, and paper birch. The dominant tree species found dispersed throughout the wetlands include black spruce, northern white-cedar, and black ash. Nearly 50 percent of the study area consists of spruce and fir stands. Peek *et al.* (1976) and Rogers (1987) provide a detailed description of the vegetation and landscape of the area.

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Approximately 6,000 individual polygons were digitized by the National Ecology Research Center (U.S. Fish & Wildlife Service). Forest compartment/stand maps [1:15,840 (4" = 1 mile)] and stand exam data were obtained from each Ranger District.

RESEARCH OBJECTIVES

The overarching objective of this research was to evaluate the trade offs of managing a section of the Superior National Forest for timber and marten. There were four specific objectives:

1 Create a habitat suitability index (HSI) model for marten to identify existing and potential marten habitat.

2 Develop a spatial model of forest vegetation capable of estimating the impacts of forest management practices on marten habitat.

3 Implement a number of simulation scenarios for analysis of the trade-offs between timber and marten habitat.

4 Generate optimal management schedules for timber that can simultaneously meet specific requirements for marten habitat.

METHODS AND MODELS

In this study, a geographic information system (ARC/INFO) and a simulation model (DTRAN) (Hoganson and Rose 1984) are used to compare the changes in pine marten habitat across time and space for a number of alternative timber harvest scenarios. Results are trade-offs between habitat carrying capacity and the Net Present Value (NPV) associated with timber harvesting on a section of the Superior National Forest. A habitat suitability index (HSI) model for pine marten was created to identify existing and potential marten habitat. The marten model is based on habitat use information that was collected from a literature review on marten and its habitat preferences.

The input for DTRAN was generated by RxWRITE (McDill 1994), a prescription writer for harvesting and forest management activities. The system provides a user-friendly interface to set up and simulate different stand management options, allowing users to specify the level of species aggregation, a range of products, potential harvest ages, thinning times, thinning intensities, and conversion options. DTRAN was used to simulate various forest development, harvest and silviculture scenarios over a 50 year planning horizon. The NPVs associated with various management scenarios were generated, using prices developed in the Minnesota Generic Environmental Impact Statement (GEIS) (Jakko Poyry 1994) for the Duluth market. In this model, the assumption was made that clearcuts occur at the beginning of each planning period. For each planning period, the HSI values were generated so that the impact of clearcuts occurring in any planning period can be examined in terms of habitat losses or gains. A real discount rate of 4 percent was used.

The information generated by the harvest scheduling model and the marten model was transferred to a (ARC/INFO). This system generated a number of maps that were used to compare changes that occurred in habitat over time and space for a number of alternative timber harvest scenarios. The display of the optimal forest management schedules in a GIS environment facilitated the interpretation of the plans, highlighted resource conflicts, and supported operational planning. The sequencing of and linkages among analysis components used in this study are summarized in figure 1.

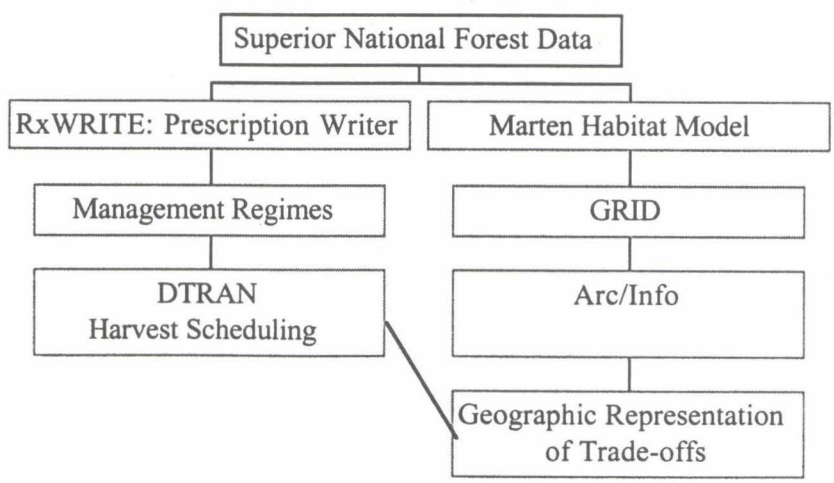

Figure 1.—*Flow diagram of the analysis process.*

A MODEL OF PINE MARTEN HABITAT QUALITY

Marten (*Martes americana*) is a fur-bearing species associated with late-successional and old-growth forests across much of North America. Loss of viable marten habitat has accelerated over the past century, ultimately resulting in partial or complete depletion of marten populations in much of the Great Lakes region. In Minnesota, marten has not been observed outside the northeastern portion of the State since 1920, and the northeastern population remained essentially flat until the early 1970's (Gunderson 1965, Stenlund 1955, Mech and Rogers 1977).

Marten populations are sensitive to habitat change due to increased logging and silviculture practices, greater human access, and unrestricted trapping. Though the species prefers mature conifer or mixed forest stands with high stocking, there have been indications that it may be capable of adapting to a variety of forest habitats that consist of mixed deciduous and coniferous species. Changes in mature forested habitat can result in significant reductions in the marten population of a given area which could, under the most adverse circumstances, lead to the eventual loss of a viable habitat for marten. Marten typically avoid large forest openings such as clearcuts. An area that is either cut or severely burned has no marten habitat value for at least 15 years, primarily because of the poor hunting conditions (Koehler and Hornocker 1977, Soutiere 1979). One researcher noted that the density of marten found in clearcut areas is one-third of the marten densities observed in a partially cut or undisturbed mature forest (Soutiere 1979). Large openings in forest cover act as psychological barriers to marten. Marten tend to restrict themselves to the more dense areas of the forest, and are unlikely to travel more than 135 m in the open.

Habitat quality for marten was calculated for a circular, 2.5 km^2 area which reflects its home range. Habitat quality was a function of the percentage of the home range covered by stands of different species types and ages. A program was developed using Arc Macro Language (AML) to represent the marten model in a GIS framework. The marten model was implemented in GRID and the trade-off analysis between timber production and marten habitat was conducted in ARC/INFO.

MANAGEMENT SCENARIOS

Three management scenarios were implemented in this study to assess the potential gains or losses in marten habitat or timber production as clearcutting was increasingly deferred over a 50 year planning horizon. Specific management scenarios were chosen primarily as case examples to examine the impact of constrained and unconstrained harvesting on marten habitat over time and space. The trade-off analysis operates on the HSI values derived for a given stand and the corresponding maximized NPV of timber associated with that stand.

An approach was explored to combine spatially scheduled timber production and the impacts on marten habitat for a large area in northern Minnesota, examining simple management scenarios in the form of delayed harvesting. The results of the analysis indicate that clearcutting over the planning horizon did not have a significant impact on the marten habitat conditions of the study area when the model is allowed to run unconstrained or clearcutting is deferred by 10 years. But significant changes in the quality of marten habitat were observed when clearcutting was constrained in the first two planning periods (Nichols *et al.* 1997).

FINAL REMARKS

The merits of the spatial approaches used in this research are that the impacts of the proposed or simulated clearcuts can be observed across the entire study area without regard to forest stand boundaries. Marten habitat is assessed in a raster based GIS (GRID), relying on neighborhood analytical procedures to predict or determine the change in habitat values after clearcuts have occurred over time and space so that the analysis of a given area is based on an evaluation of the spatial habitat requirements of the marten without regard to arbitrary administrative delineations or boundaries. The availability of modeling capabilities in ARC/INFO enabled a level of spatial analysis used to examine the impacts of clearcutting on marten habitat.

As large tracts of contiguous old-growth forests vanish due to natural or human-made causes, there will be greater incentive to strengthen existing planning efforts to include wildlife resources in management evaluations of public lands. The use of technology as illustrated in this paper is becoming an integral part of the planning processes pursued on our national forests.

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AN OPTIMAL FORAGING MODEL FOR THE RED-COCKADED WOODPECKER

W.J. Coles, David Hughell, and W.D. Smith[1]

ABSTRACT.—Various means have been used to estimate the territorial needs of the red-cockaded woodpecker. In this work we propose a model derived using optimal foraging techniques and avian energetics as a means to assess the viability of even-age stands of pines as red-cockaded woodpecker foraging territories.

The red-cockaded woodpecker (rcw), once abundant in the southeastern United States, has suffered severe reduction in numbers as the mature pine forests, which are its preferred habitat, have been reduced by clearing, logging, and fire suppression. In 1970 the species was officially declared endangered; since that time the rcw has been studied intensively, at least partly with a view to estimating territorial requirements and population sizes required for survival (U.S. Fish and Wildlife Service 1985; Ligon *et al.* 1986; Walters 1990, 1991 and references therein).

We have not seen in the literature any attempts to relate directly the viability of a territory as rcw habitat to the vital processes of the bird; this may be due at least partly to the difficulty of quantifying the presence of arthropods in a forest environment (Dahlsten *et al.* 1990). Recently, however, R.G. Hooper (1996) has given empirical equations in terms of tree and stand parameters for pine boles and for arthropod densities on southern pines. Using Hooper's equations and parameters derived from avian energetics, we offer here a way to compare suitability of even-age stands of pines as rcw foraging territories.

THE OPTIMAL FORAGING MODEL

We consider an even-age stand of pines to be a patchy foraging area, each pine being a patch, and apply optimal foraging theory to maximize the net metabolic energy an rcw is able to achieve within the constraint of a fixed amount of foraging time within a 24-hour period. We assume that the pines are evenly spaced, of equal height and diameter, and bearing equal densities of arthropods as prey, and that the understory is of uniform height, but we see no reason why the analysis cannot be extended to stands not of even age and also with variable prey densities.

Following Repasky (1984), we idealize the bird's foraging pattern as follows: the rcw flies in a direct line from the top of a pine to alight on a next pine at understory height, hitches directly to ground level without seeking prey, and then hitches, meanwhile seeking and capturing prey, to the top of the pine. The cycle is then repeated until the allotted foraging time is exhausted (fig. 1). This may, on the face of it, seem like a strange way to forage a pine, particularly in an optimality model, but is close enough for our purposes to the actual foraging behavior of the woodpecker and in addition has striking similarities to an optimal pattern discussed by Norberg (1983).

Let T denote the total time allotted for foraging, n the number of trees foraged, t_o the fixed time (the flight time plus the downhitching time) in the cycle for one tree, and t the variable time spent uphitching while seeking prey.

Then

$$T = n(t_o + t).$$

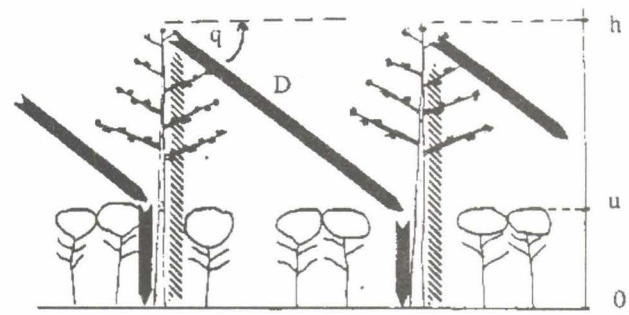

Figure 1.—*Foraging pattern of the red cockaded woodpecker.*

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The Cost Per Tree

The cost per tree C(t) is given as the sum of the fixed cost C_F and the variable cost $C_V(t)$. For the rcw we derive the hitching metabolic rate of 1.88 joules per second from the allometric equation

$$FMR = 18.2M^{0.749} \text{ (units are W. and kg.)}$$

given by Nagy (1987) for the field metabolic rate for passerine birds, with the result that

$$C_V(t) = 1.88\ t.$$

The fixed cost C_F is the sum of the flight cost C_{FL}, the downhitching cost C_H, and the cost C_{PE} of the potential energy gained by climbing to the top of the pine. Taking the weight of the rcw to be 0.47 Newtons (Repasky) and converting mechanical power to metabolic power by the factor 4.35 (Pennycuick 1975) gives

$$C_{PE} = 2.06\ h,$$

where h is the pine height. The flight cost is obtained by converting Repasky's expression for the mechanical power of flight for the rcw to a metabolic rate and adding a standard metabolic rate calculated from the allometric equation

$$SMR = 6.83\ M^{0.704}$$

of Aschoff and Pohl (see Norberg, U.M. 1990, p. 43). This gives

$$C_{FL} = (D/12)(0.81 + 4.35\{0.1\cos^2 q + \max[0, 0.9 - 5.6\sin q]\}),$$

where D is the slant flight distance from the top of a pine to the next pine at understory height, q is the angle below the horizontal of the flight path, and the factor D/12 is the time the rcw takes to cover the distance D at 12 m per second, its most economical flight speed (calculated by Repasky from formulas in Pennycuick).

Estimates of Fedak *et al.* (1973) and Tucker (1970) imply that running cost per meter for birds is 9 times the most economical flight cost, which estimate Repasky takes for the hitching cost for the rcw. This estimate, together with our assumption of the FMR of 1.88 joules per second as the metabolic cost of hitching, imply that the hitching velocity of the rcw is 0.328 m (12.9 in.) per second. We are not aware of any data-based estimate of the downhitching velocity of the rcw, but this value seems high to us, and since Repasky himself remarks that hitching, being a jerky movement that involves changes in kinetic energy, is no doubt more expensive than running, we take our hitching cost estimate to be 11 (rather than 9) times the economical flight cost. This produces an estimate of 0.268 m, or 10.6 in., per second for the hitching velocity, and the incremental metabolic cost of downhitching a distance u, the height of the understory, turns out to be 3.98 u. The standard metabolic rate of 0.81, divided by the rate of hitching (0.268 m per second) gives the rate of energy per meter and so contributes 3.02 u, and the total downhitching cost is

$$C_H = 7u.$$

Finally, then, the total cost function per tree is given by

$$C(t) = C_F + C_V(t) = 2.06h + 7u + (D/12)(0.81 + 4.35\{0.1\cos^2 q + \max[0, 0.9 - 5.6\sin q]\}) + 1.88t.$$

The Gross Gain Per Tree

We assume that the rate of increase of the gross gain function G(t) decreases exponentially as time increases, that is, for some constant k,

$$G'(t) = ke^{-rt},$$

that G(0) = 0, and that G(t) approaches the total amount M of prey (expressed in joules of metabolic energy) as t grows large. With these assumptions, integration of the equation for G'(t) yields

$$G(t) = M(1 - e^{-rt}).$$

The parameter r is the relative rate with respect to time of capture of prey; to see this explicitly, notice that M - G(t) is the amount of prey remaining after elapsed time t and that

$$G'(t) = rMe^{-rt} = r(M - G(t)).$$

Now let B, p, and c denote, respectively, the pine bole in square meters, the prey density in grams dry weight per square meter, and the factor which converts grams (dry weight) of prey to joules of metabolic energy for the rcw. Then M = cpB and so

$$G(t) = cpB(1 - e^{-rt}),\ t \geq 0.$$

The conversion factor c is taken to be 17.22 (Bell 1990). Hooper's empirical equations estimating B and p are

$$B = -17.1528 + 1.0899Dbh - 0.3596h,$$

where the diameter at breast height is in cm and the pine height h is in meters, and

$$p = 10^{-3}(211.88 - .006687A^2 - 6.4433R),$$

where A is the age in years of the pine and R is the radial increment in mm from 10 years prior time to 5 years prior time.

Optimization of the Total Net Energy Gain

The net energy gain per tree is $N(t) = G(t) - C(t)$, and the total net energy gain is

$$E(t) = nN(t) = TN(t)/(t + t_o).$$

The value t^* of t which maximizes E(t) must satisfy $E'(t) = 0$, or equivalently,

$$(t + t_o)N'(t) = N(t).$$

For our expressions for G(t) and C(t) this simplifies to

$$Mrt + M + Mrt_o = (M + 1.88t_o - C_F)e^{rt},$$

whose unique positive solution t^* must be found numerically.

To show that there indeed is a unique positive t^* unless the rcw cannot even make expenses in the stand, we define the functions f(t) and g(t) by

$$f(t) = Mrt + M + Mrt_o,\ g(t) = (M + 1.88t_0 - C_F)e^{rt}$$

(the left- and right-hand sides, respectively, of the equation defining t^*). Since Mr is the maximal rate of accumulating and 1.88 is the rate of energy expended while foraging, we must have

$$Mr > 1.88$$

for the stand to be viable, so that

$$f(0) = M + Mrt_o > M + 1.88t_o > M + 1.88t_o - C_F = g(0)\ ;$$

that is, at $t = 0$ the graph of $y = f(t)$ starts out above the graph of $y = g(t)$.

Further, since the total amount M of prey available must be greater than the fixed cost C_F of foraging for the bird to have a chance of making a living, we must have

$$g(0) = M + 1.88t_o - C_F > 1.88t_o > 0.$$

Since $y = f(t)$ is a straight line and $y = g(t)$ is an exponential curve with positive coefficient and positive exponent, and since by the above analysis the graph of $y = f(t)$ starts out above the graph of $y = g(t)$, the graphs have a unique point of intersection for $t > 0$, so the value t^* that maximizes the total net energy E(t) is positive and unique (fig. 2).

Finally, using the equation defining t^* to get the next-to-last of the following equalities, we have

$$E(t^*) = nN(t^*) = TN(t^*)/(t^* + t_o) = TN'(t^*) = T(Mre^{-rt^*} - 1.88).$$

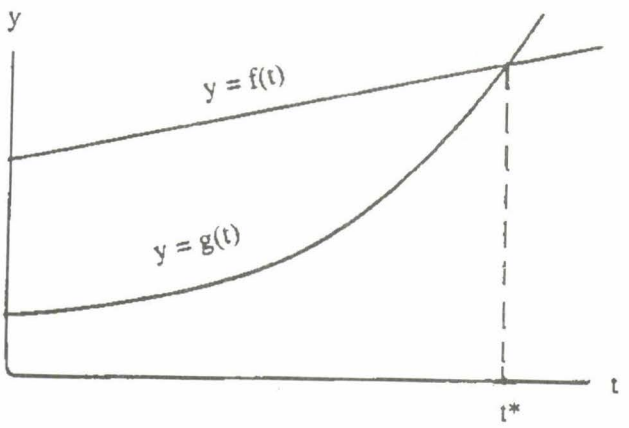

Figure 2.—*Intersection of $y = f(t)$ and $y = g(t)$ yielding t^* that maximizes E(t).*

DISCUSSION

The model needs to be validated against existing data. This is particularly true of the relative rate of predation r. Just as quantification of arthropods has proved to be difficult, so, it seems, has estimation of r in general and in particular. Feasible parameter ranges might be obtained by measurements of prey consumed relative to prey present as given by Hooper's empirical equations giving boles and prey densities.

We are fully aware that application of optimal foraging theory, both in general and in particular to foraging behavior in birds, has both its adherents and its detractors (Maurer 1990, 1996; Stephens 1990). We emphasize here that we make no claims that the rcw makes any decisions, either consciously or unconsciously, to forage using the strategy we have described (we do suggest, however, that whether the bird indeed does forage in a way that to some degree approximates this strategy could be tested in the field). Likewise, we make no assertions regarding population demographics, since the model includes no birth or death processes or incremental energetic requirements because of seasonal variations or breeding requirements for the bird, or any population dynamics for the prey. What we do suggest is that the maximal energy $E^* = E(t^*)$ available to a single rcw foraging an even-age stand during a fixed time T, using this optimal foraging strategy, might be useful as an index of viability for such a stand as a foraging area.

We have already pointed out that if $Mr \leq 0$ the stand might be thought inadequate as a foraging area; the same conclusion might be drawn if we find that if $E^* \leq 0$, that is, even using a strategy defined as optimal under our assumptions the basic costs of foraging outweigh the benefits to be gained.

Even if the E^* which our analysis yields is negative, since the bird might not forage optimally the stand might

not qualify as a foraging area. In addition, we have not included fixed costs F such as travel, defense, and so on. They would depend on the particular stand in ways that do not enter into our analysis; they are independent of t and so do not affect the value of t*, but should be incorporated by using E* - F rather than E* as the true viability index, so that a necessary (but not sufficient) condition for viability is

$$E^* - F \geq 0.$$

Of course, if n* is the number of trees corresponding to t*, a further necessary condition would be that the stand contain n* pines, or kn* pines to support communal foraging by a group of k birds.

In the above senses, then, E* - F provides a quantitative estimate of viability. However, even if the above necessary conditions are not met, E* - F would provide a qualitative estimate for comparing the value of different stands as possible foraging areas for a single rcw.

Finally, our model estimates the desirability of even-age stands as foraging area in a way that involves avian energetics but whose use requires knowledge only of stand parameters that can be both measured in the present and estimated for the future. We hope that the index derived by its use, together with other methods to assess territorial suitability, will prove useful in making the management decisions necessary to provide for not only an adequate harvest of timber but also the continued existence of the red-cockaded woodpecker.

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USING OBJECTIVE FUNCTION PENALTIES TO ELICIT OWL AND LATE SERAL CAPABILITIES

L. Russell Fletcher[1]

ABSTRACT.—This paper addresses the issues of modeling northern spotted owl (*Strix occidentalis caurina*) habitat and late seral conditions within the long-term forest ecosystem management plan. The results presented here are from management plans constructed for several large northern California management units using the ecosystem planning express, or **Ep(x)** analysis process developed by VESTRA Resources. Before incorporation of the owl and seral policy constraints into the final preferred alternative linear program run, we first developed a set of strategies and objective function formulations designed to elicit owl and late seral acres for various periods in the planning horizon, primarily to see what the model was capable of producing in those periods or groups of periods. Final policy constraints were then revised based on this knowledge. The results of this strategy were that the landowner and wildlife policy analysts were able to more efficiently converge on the objectives of timber harvest and wildlife protection, and to save countless hours of linear programming run time.

INTRODUCTION

Forest planning has progressed through the years from managing for timber production, to managing for multiple use, to managing for the total forest ecosystem with wildlife habitat preservation and enhancement progressing to the top of the forest output priorities (Fletcher 1997). Timber harvesting is now more a byproduct of the forest ecosystem plan, especially on public lands. And, this planning process is not peculiar just to public lands. American society is increasingly viewing forests as a public trust resource regardless of ownership (Davis and Barrett 1992).

The forest planning models have also transitioned along with these changes in planning priorities. They have progressed from the classical fully regulated, continuous yearly flow models of area regulation (Davis and Johnson 1987) prior to the 1960s, to the mathematical programming/optimal harvest schedule models (Johnson and Sheurman 1977, Davis and Johnson 1987) from the 60s to mid-80s, to the current strategy available in the Spreadsheet Assisted Resource Analysis (SARA) model (Davis *et al.* 1991) of prescribing specific ecological health prescriptions to specific land areas and evaluating the resultant schedules of total forest outputs including vegetation structure, wildlife suitability, timber harvest, water quality, and recreation. FORPLAN (Johnson *et al.* 1986) and Spectrum (Sleavin 1994) also provide similar levels of model input and output analysis.

The enhancement and maintenance of wildlife habitat and late seral conditions in the forest ecosystem environment have been perplexing issues for those in both the public and private sectors who are charged with the stewardship of forest lands. To model these often enigmatic goals, one must first define in algebraic terms the relevant parameters that define the particular habitat types and conditions. Thus model output, typically a linear programming (LP) solution, are only as valid and as useful as the input formulations from which they are generated. In addition, a high level of validation in the form of ground-truthing needs to be done prior to issuing this final definition set. And assuming that the definition set is valid, how does the wildlife analyst then determine what percentages of each of the nesting, roosting, and foraging habitats will be required throughout the management unit? This latter determination probably has the greatest effect on the landowner in terms of harvest flow or present net worth of the land, and in this litigious area of natural resource planning, these determinations must often be justified in a court of law.

In California, the timber industry has been quick to respond to increasing demands on their lands by both regulatory bodies and environmental groups (Fletcher 1997). Specifically, the California Department of Forestry's sustained yield plan (SYP) option for private

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timber holdings greater than 50,000 acres, if selected, requires that a long-term plan be submitted by each landowner which addresses, among many other considerations, the specific issues of wildlife habitat and late seral protection and enhancement. These issues must be addressed at both the individual watershed and management unit levels. In response to this total ecological and economic planning environment, the ecosystem planning express, or **Ep(x)**, modeling process was developed by VESTRA Resources (VESTRA 1997, Olson *et al.* 1997). The **Ep(x)** process utilizes geographic information systems (GIS), data base, and linear programming technologies to formulate a long-term management plan while addressing the various goals of the landowner, regulatory agencies, and the public trust. One of the key features afforded by the **Ep(x)** technology in dealing with these complex and multi-level constraint sets is the ability to perform high volume, multiple run set, post-optimality sensitivity analyses which do not involve reformulation of the entire problem.

METHODOLOGY

Many of the long-term planning projects at VESTRA involve sizeable management areas, some exceeding 200,000 acres. Although large area does not, by itself, pose problems for LP size, the large number or areal units singled out for special concern and additional constraint development results in a large number of land type/silvicultural prescription combinations (decision variables)—one recent project involving constraints over 25 watersheds resulted in an LP with over 350,000 columns and 15,000 rows. Ultimately, this project precipitated development of much of the technology presented in this paper, primarily as a response to limits on computational feasibility—a problem of this size can take over 5 hours of LP run time on an Intel Pentium Pro 200 PC with 128mb RAM.

After defining vegetation types, size classes and crown closures which best characterize owl[2] and/or late seral habitat, the wildlife analyst(s) then specifies the desired percentages of each to be attained for each watershed in the management unit and for the unit as a whole. These constraints, occasionally accompanied by existing watershed acres in these habitat types, are then presented to the operations research analyst for inclusion into the LP model. As alluded to earlier, it is generally these types of constraints that almost always render the LP problem infeasible, and generally in such a massive way that it is often impossible to detect the real underlying causes of those infeasibilities. And at 5 hours per LP run, it could take weeks to sort out just what is achievable in each watershed and at what time period. And, of course, the customer wants the results the next day. The solution to this dilemma is to develop a set of pre-processing algorithms and routines that will better identify the behavior of these habitats as they progress through the long-term planning horizon. These results are then conveyed back to the wildlife analyst(s) and/or planner(s), and after a number of such iterations a final set of feasible habitat constraints can then be finalized for the preferred LP run. We have developed such a module as part of our overall planning model **Ep(x)**. This module, called REVISE, contains a number of subroutines which allow for batch processing of multiple alternative LP runs. These specific subroutines allow us to quickly develop and solve the following types of LP run sets:

1. Goal programming where both present net worth (PNW) and minimum habitat variances are maximized simultaneously,
2. Maximize owl and/or late seral habitat types either discounted or non-discounted,
3. Sequential linear programming (SLP) maximizing owl and/or late seral habitat types, and
4. Run LPs at different percentages of habitat retention to show effect on PNW and/or harvest.

In addition, we can execute database queries on maximum habitat achievable per period not conditional on the maximum habitat achievable in the previous period.

Ep(x) POST-OPTIMIZATION SENSITIVITY ANALYSIS

The **Ep(x)** process from the initial problem development through the first LP run is explained in detail in the literature (VESTRA 1997, Olson *et al.* 1997). One of many differences between **Ep(x)** and other long-term planning models is that, in **Ep(x)**, the LP output is not the "final" or "preferred" scenario optimization solution. Rather it is the beginning of a process that uses an initial solution of a LP, which has been formulated to include all relevant constraint sets and special concerns (wildlife, seral stage, viewshed, etc.), along with the **Ep(x)** routine REVISE which allows the analyst to then select the ranges and increments over which the constraint set(s) are to be varied. These changes are all applied directly to the final tableau of the initial LP run (VESTRA Resources uses the C-WHIZ solver from Ketron Management Science, and their final tableau is called the Actfile). In addition to varying the constraint sets, the REVISE routine is also capable of selecting single or multiple objective functions. The **Ep(x)** MPS generator (MPS is the input format required by C-WHIZ) also allows inclusion of all possible objective functions as well as the constraint sets. It is irrelevant for the initial LP run which objective function is selected.

[2] *Throughout this paper the owl habitat type referred to is nesting, and does not include roosting or foraging.*

The graphical user interfaces used in the REVISE routine for varying the constraint and objective settings are depicted in figures 1 and 2, respectively. Figure 3 shows the flow through the REVISE routine. Briefly, in figure 1 a constraint value setting can be constant, vary/constant or vary/vary. If constant is checked then the constraint value is always set at the default value. The vary/const option varies the constraint value between the LO and UP range at the specified increment, with all other constraint settings held at their default values. A vary/vary selection (only one such selection allowed per run set) varies that constraint setting as with the vary/const check, however these settings will continue to vary over all other constraint sets for which the constant or vary/const options are selected. Thus, for example, if the boxes are checked as in figure 1, there will be a total of 75 run changes generated by REVISE which will be output to a database table having 75 record sets, each of which will then be converted to a separate MPSIN file (MPSIN is the C-WHIZ routine which makes changes directly to the Actfile and then reruns the LP without having to reformulate the problem). **Max. hvst dec. percent** is varied between .5-.7 (3 values), **Min. net rev** is varied between 20-25 (6 values), and **Min. owl hab percent** is varied between 0-.5 (6 values). This is a total of 15 changes, however with the **Min. late seral percent** varied between 0-.2 (5 values) each of these 15 vary/const changes is also varied 5 times over the ranges of **Min. late seral percent**, since it is checked vary/vary, for a total of 75 changes.

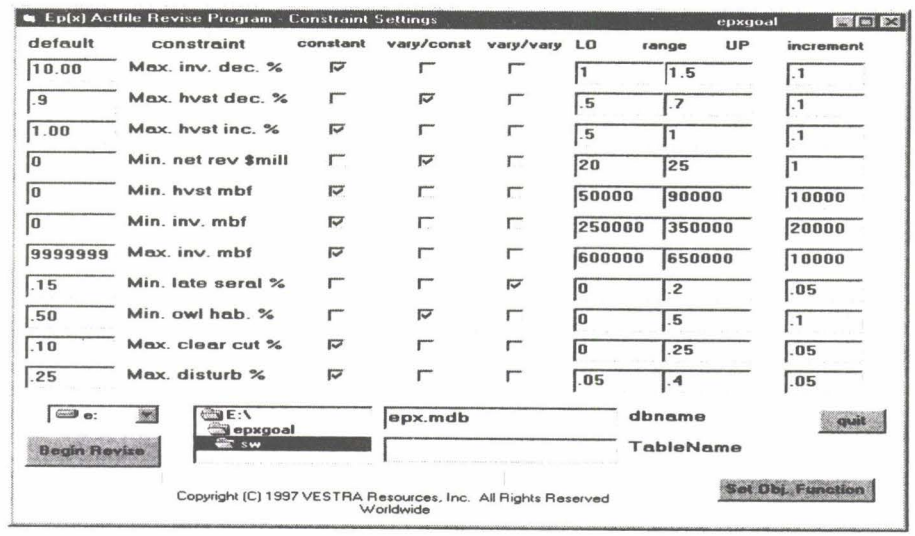


Figure 1.—***Ep(x)*** *REVISE constraint range setting interface.*

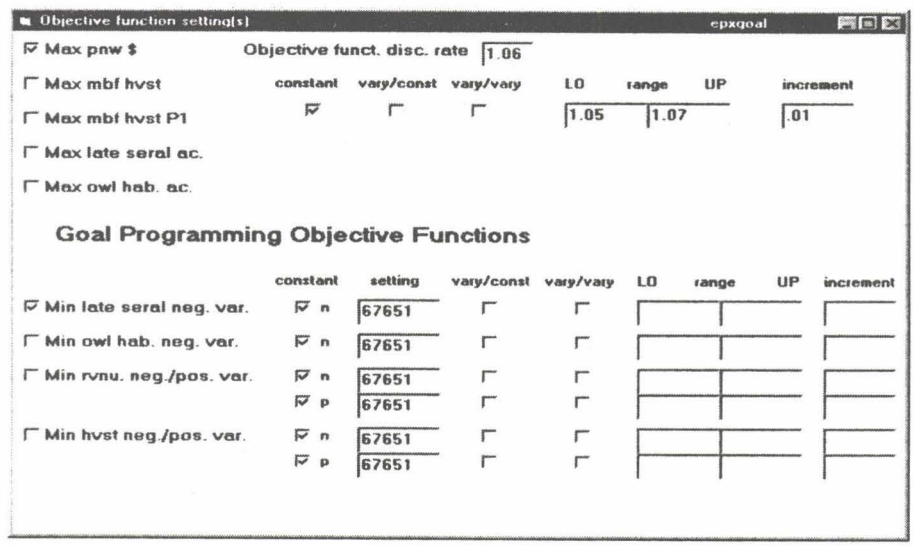


Figure 2.—***Ep(x)*** *REVISE objective function selection interface.*

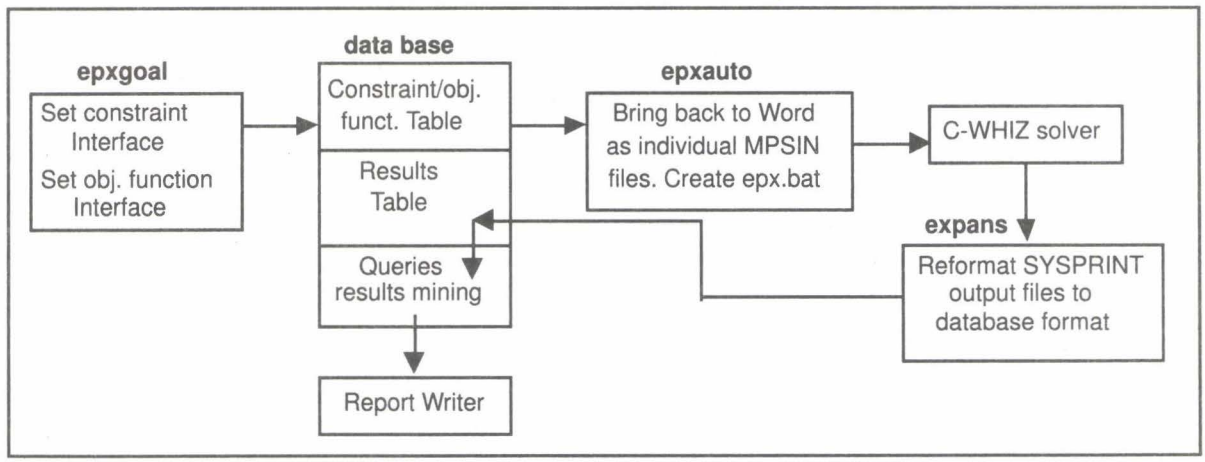


Figure 3.—***Ep(x)*** *REVISE post-optimization sensitivity analysis routine.*

GOAL PROGRAMMING APPROACH

In the objective function setting interface depicted in figure 2, individual and/or simultaneous goal and standard objective function selection can be accommodated, along with a discount rate selection. Often omitted in the literature on goal programming is that standard (top of fig. 2) objective functions can still be optimized along with the goal programming objectives (bottom of fig. 2) if the analyst is careful in selecting the goal weights. For instance, one might want to minimize late seral and/or owl habitat variance from a desired level. If these are the only decision variables in the objective function, then the LP will terminate when this variance has been minimized. There is no reason that we cannot also and simultaneously maximize profit. Simply setting the goal weight(s) greater than the highest revenue contribution per acre of any combination land type and silvicultural prescription does this.

In the example from figure 2, the goal weights begin at 67651 for this management unit because the largest contribution to net revenue from any acre in any period is $67,650. This objective function is formulated as follows:

Maximize $Z = \sum_{i=1}^{n} d_i R_i - \sum_{i=1}^{n} PD_i$ where

n = number of periods in planning horizon
d_i = discount in period i
R_i = net revenue in period i = $\sum_{j=1}^{m} \sum_{k=1}^{p} a_{jk} L_j S_k$
m = number of land types in management unit
p = number of silvicultural prescriptions available to each land type
a_{jk} = net revenue contribution per acre of land type L_j using silvicultural prescription S_k
P = penalty weight per acre of late seral below desired level
D_i = dummy late seral acres in solution to achieve desired level in period i, and
$P > a_{ijk} L_j S_k \forall i$

Thus, in the LP it will always be most optimal to achieve all the late seral acres desired, if they exist, throughout the range of land type/prescription combinations and subject to the limitations of other constraint. The accounting variable PNW is then set:

$$PNW = Z + \sum_{i=1}^{n} PD_i, \text{ or } = \sum_{i=1}^{n} d_i R_i$$

to retrieve the maximized PNW since the objective function value Z is not very useful.

MAXIMUM TEMPORAL HABITAT QUERY SETS

The quickest way to discern what levels of habitat will be potentially available over the planning horizon, is to do a database query by period of the maximum available habitat acres achievable by all land types over all prescriptions designed to produce those specific habitat types. This is done independent of the prescriptions selected by the query for those land types in the preceding period. In this manner the results will never be achievable since only a single prescription can be assigned for the entire planning horizon for each land type, however they do show the potential for habitat acres in any particular period as well as uncovering any arithmetical modeling problems within the database. Figures 4 and 5 show the results of one such query for owl and late seral acres. These queries can be done at both management unit and watershed levels, and are some of the first quality control steps in the **Ep(x)** modeling process. Figure 4 illustrates the typical response one would expect in this type of planning environment. Figure 5, however, shows a potential decline in late seral acres in periods 9 and 10. This

anomaly is not supported by the silvicultural prescriptions set up in the growth and yield modeling process, which were designed to produce late seral acres. In this instance we were using the California Wildlife Habitat Relationships System (WHR) (Airola 1988, Mayer and Laudenslayer 1988, Zeiner *et al.* 1990) to determine late seral acres, and specifically the classes 5D, 5M and 6. These are stands with trees >24 inches dbh and ≥ 40 percent canopy closure or multi-layered stands with size class 5 trees over a distinct layer of size class 3 or 4 trees and a total canopy closure ≥ 60 percent. In the growth and yield modeling process, it is the latter size class 6 which, due in part to the influx of new growth, can vacillate between a size class 6 and size class 4 which then takes the acreage out of the late seral category. This is, in fact, what had occurred and we were able to correct the problem at this early stage of the planning process.

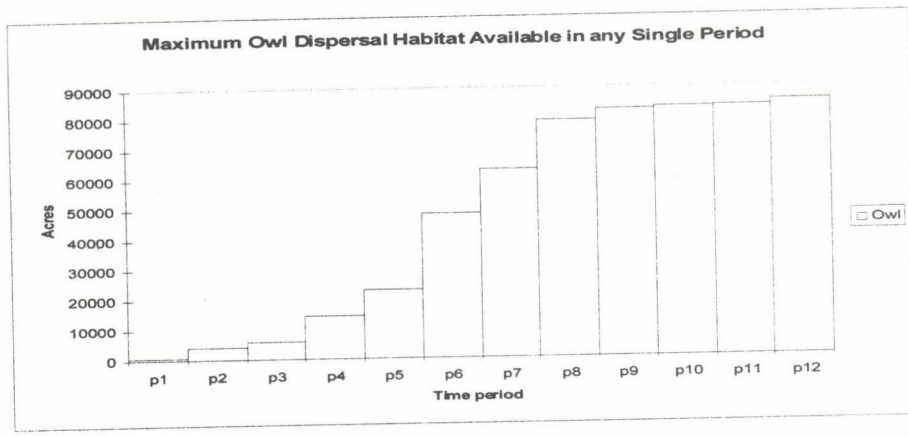


Figure 4.—*Temporal availability of unconditional owl habitat acres.*

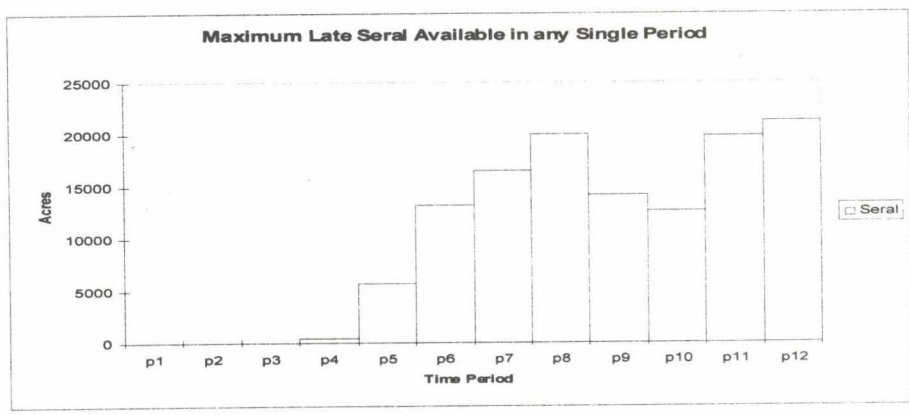


Figure 5.—*Temporal availability of unconditional late seral habitat acres.*

SENSITIVITY OF PNW AND HARVEST LEVELS TO CHANGES IN HABITAT REQUIREMENT

The sensitivity of PNW and harvest percentage changes (which follow PNW closely) to minimum percentage late seral retention can be seen in figure 6. As expected, the change in PNW is dramatic up to about 25 percent late seral at which point the problem usually becomes infeasible. For any number of large timber holders, this reduction in PNW can reach well into the hundreds of millions of dollars. This is also one of the first charts we feed back to the wildlife analyst(s), not for purposes of affecting any changes in habitat retention, but rather to drive home the point that there is little room for arbitrariness in their determinations

Figure 6 is also derived using the **Ep(x)** REVISE routine. Referring back to figure 1, we would have checked the **Min. late seral percent** vary/const box and specified a LO/UP range of 0-.25 with an increment of .01, for a total of 26 runs. The original formulation of this problem for any given late seral percentage would have taken approximately one hour and fifteen minutes to solve, with the MPS file already having been generated. Using the REVISE routine, however, and solving from the most to least restrictive late seral percentages, each REVISE run took approximately fifteen minutes of solution time with no set up time between runs (REVISE generates it's own batch file for continuous processing through C-WHIZ).

MAXIMIZING OWL AND LATE SERAL HABITAT

In addition to querying the database for maximum habitat achievable for single periods, it is also useful to maximize total habitat acres conditional on the habitat acres of previous periods. This can be done in several ways: maximizing discounted and non-discounted habitat or using SLP to maximize first through final period habitat separately, holding prior period solution habitats constant for subsequent period optimization. These runs are generally set up with all other constraints relaxed. Figure 7 shows the results of these three run sets. As expected the non-discounted run produced the most late seral acres overall, however the discounted run brought those acres up faster through period 8. The SLP run brought late seral acres up the fastest through period 6 and then fell below the others for the rest of the planning horizon. The wildlife analyst(s) and policymaker(s) could use this information along with results from other sensitivity runs to develop the final resource and policy constraint sets.

CONCLUSIONS

Using the strategies developed in this paper, along with the **Ep(x)** sensitivity routine REVISE, we were able to perform many such analyses both as a quality control technique and subsequently, as a wildlife and policy strategy setting tool. These types of analyses are also used to look at many other critical LP constraint sets such as maximum disturbance index percent allowed, maximum clearcut area as a percentage of total area, maximum period harvest decrease percentages, inventory levels and many others.

The automated generation and subsequent processing of the MPSIN files on the Actfile, and subsequent output of these LP's directly to the database, create a new environment in LP modeling. The analyst can now generate hundreds or thousands of LP runs in batch mode, and analyze the outputs through a series of database queries, selecting an appropriate subset of LP results for subsequent manual perusal. As an example, on one such REVISE run set, we were able to generate and solve 819 LP runs in just less than 12 hours. The actual time to generate the MPSIN files and batch file from interface through the database and back to Word for input to the C-WHIZ solver (see fig. 3) took less than 2 minutes. The analyst then initiated the epx.bat file, left for the evening and returned the next morning to begin the database

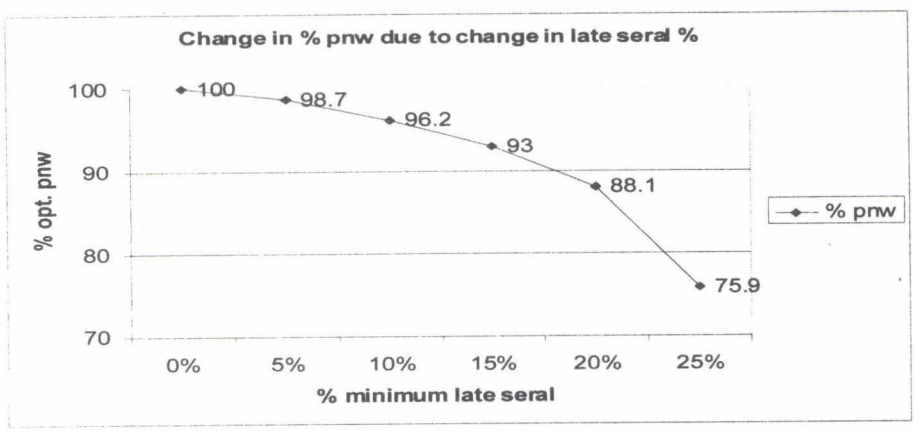
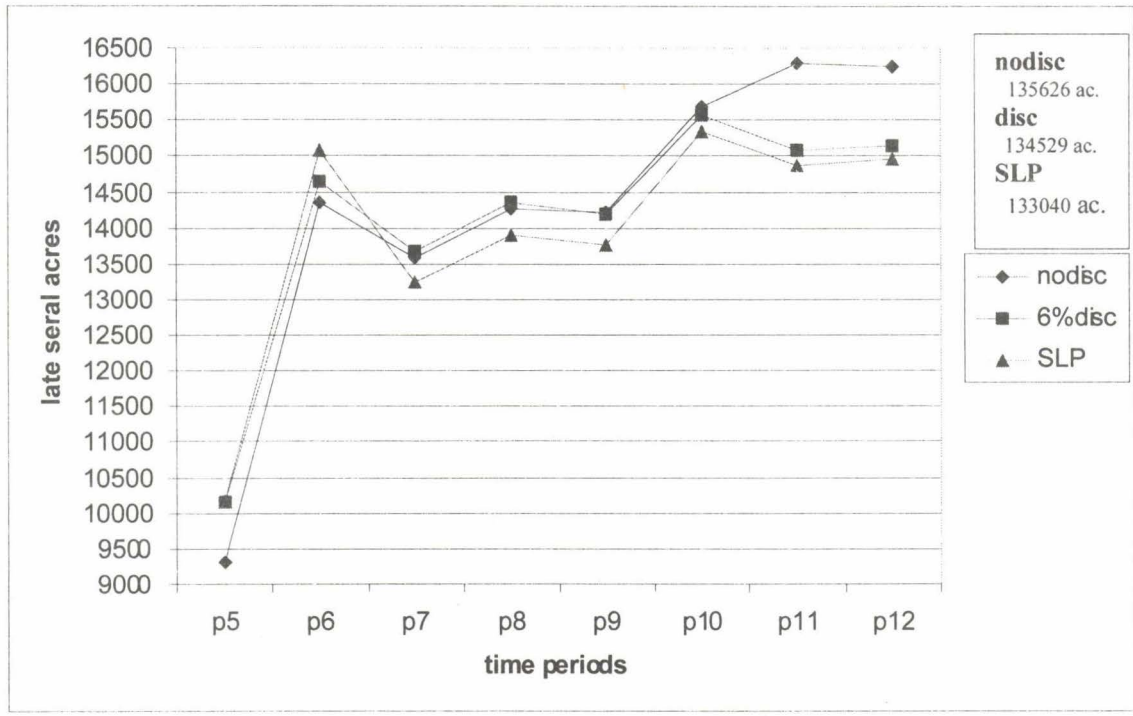


Figure 6.—*Change in percent PNW due to change in late seral percent.*



	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	p12
nodisc	1387	5567	6185	8530	9306	14345	13588	14256	14223	15690	16296	16253
disc	1387	5598	6185	8530	10154	14650	13687	14355	14199	15565	15068	15151
SLP	1387	5598	6185	8530	10167	15068	13245	13913	13757	15351	14866	14973

Figure 7.—*LP maximization of late seral acres.*

queries on the completed 819 LP runs. This type of LP batch processing and sensitivity analyses on critical and controversial forest ecosystem parameters becomes more relevant as more and more special interest groups attempt to influence the decisionmaking process.

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SIMULATED ADAPTIVE MANAGEMENT FOR TIMBER AND WILDLIFE UNDER UNCERTAINTY

David A. Hughell and Joseph P. Roise[1]

ABSTRACT.—A spatially explicit stochastic behavior simulation model for the endangered red-cockaded woodpeckers (*Picoides borealis*) is coupled with a forest management optimization algorithm to simulate adaptive (feedback) management within an uncertain environment. To update the adaptive forest harvest schedule in a timely manner during each management planning period, a genetic algorithm heuristic is employed. This model is used to evaluate management policies for the production of timber and red-cockaded woodpeckers.

Forest management plans are typically based on an "optimal" activity schedule which can be rendered infeasible during implementation due to changes in the resources being managed and management goals. Thus in practice, such an activity schedule is evaluated periodically during implementation, and is often replaced with a newly generated "optimal" schedule. This paper describes an analytical tool for evaluating management strategies that take into account this adaptive implementation of activity schedules.

Computer simulation models offer valuable, and often the only, tools for testing and examining intricate theories concerning the response of wildlife to management activities. This is especially true for species that depend on a variety of resources in specific spatial patterns at the landscape level. In this study a spatially explicit wildlife behavior simulation model is coupled with forest management optimization algorithm to simulate adaptive management (feedback) for timber and wildlife benefits. Uncertainty is introduced into the system through the stochastic simulation of changes in the spatial distribution of red-cockaded woodpecker (*Picoides borealis*) (RCW) groups. The changes in the distribution of the RCW groups influence the decision options for forest management optimization, and forest harvest activities influence the distribution of RCW groups. This results in a feedback loop between simulated wildlife behavior and forest management. To generate near optimal forest harvest schedules in a timely manner, a genetic algorithm (GA) optimization heuristic is applied. The result is a feedback system between RCW groups and forest management actions.

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This modeling system (Hughell 1996) is used to evaluate adaptive management policies and optimization strategies over a 200-year planning horizon. The management policies define each stand's minimum rotation age as a function of the stand's proximity to a RCW group. The optimization strategies are volume control and the utilization of explicit 200-year near optimal harvest schedules (generated by a genetic algorithm).

RCW GROUP BEHAVIOR / FOREST MANAGEMENT MODEL

The red-cockaded woodpecker (*Picoides borealis*) (RCW), an endangered species associated with the coastal pine forests of the southern U.S., is considered a cooperative breeder because of the manner in which it nests and forages in family groups (which consist of a breeding pair and reproductively mature helpers) (Walters *et al.* 1988). RCW prefer to nest in live Longleaf pine (*Pinus palustris*) trees over 95 years of age, or in Loblolly pine (*P. taeda*) over 75 years, although they have been found in much younger trees (Hooper 1988).

The RCW group behavior/forest management model[2] grows even-aged longleaf pine stands, simulates the behavior of RCW groups and harvests stands based on specified management schemes. The forested landscape is modeled as a lattice of 4-hectare hexagon cells. Each stand is grown and RCW foraging suitability (birds/hectare) is calculated accordingly. RCW behavior and stand development are simulated in 5-year iterations, nested within 20-year forest management cycles which harvests stands based on their current condition and proximity to RCW nesting groups (fig. 1).

[2] *The source code (Borland C++) are available upon request to Dr. Joseph Roise (email: roise@cfr.cfr.ncsu.edu).*

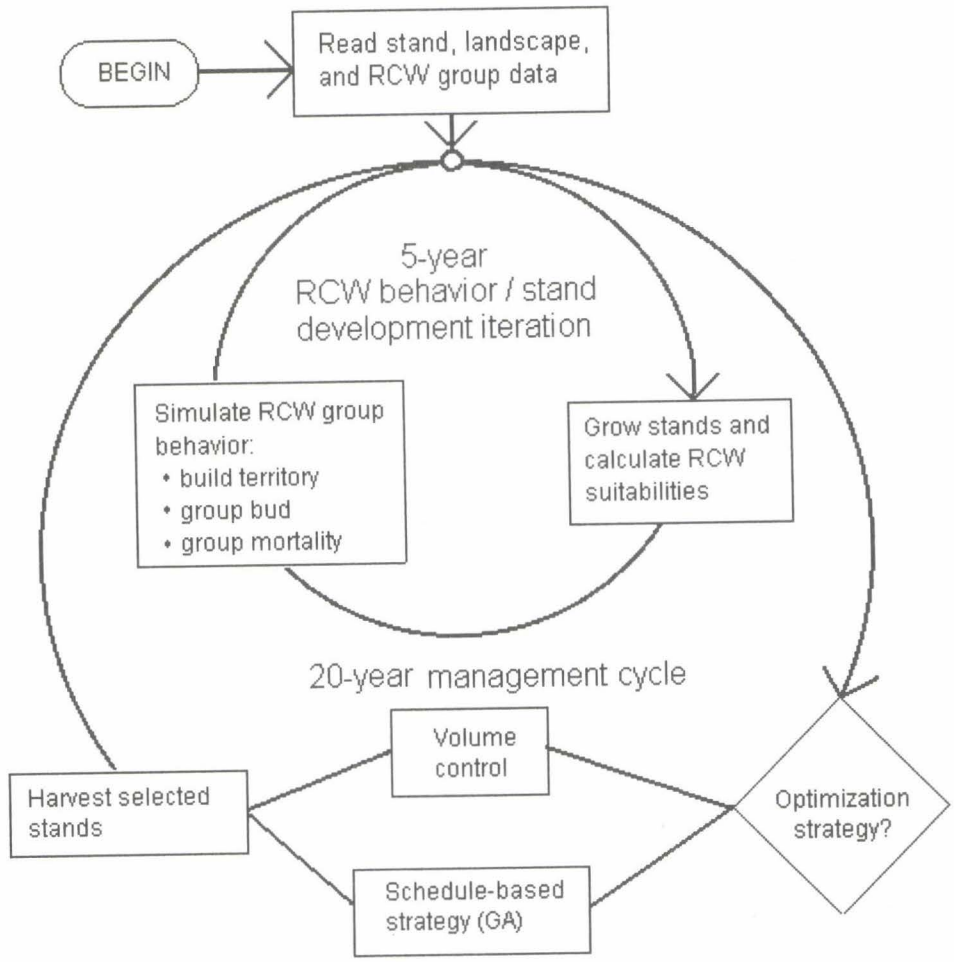

Figure 1.—*Flow diagram for the RCW group behavior/forest management model.*

RCW Group Behavior Simulation

At the beginning of each 5-year RCW behavior iteration, deterministic equations based on stand age and site index project the wood volume and RCW foraging suitability. The equation for estimating the foraging resources is based on a RCW energy-cost territory viability model developed by Smith and Coles (1993). Because creation of RCW foraging habitat is a benefit provided by standing trees (as opposed to a benefit realized only when the trees are harvested), the parameter of interest for the evaluation of different rotation ages is the cumulated flow of foraging resources up to when the stand is harvested (Hartman 1976). Therefore, compatible equations were developed for estimating the current foraging resources (for RCW behavior simulation) and accumulated foraging resources (for management planning).

The optimal single-stand rotation age based on the culmination of the mean annual increment is 30 years for timber and 110 years for RCW foraging resources. Based on this information, the theoretical tradeoff between timber and RCW is obvious—harvest as early as possible for timber and harvest at 110 years for RCW. However, the true situation is more complex once the distribution of the stands through time and space is taken into account.

The wildlife simulation model abstracts the behavior of RCW groups down to three activities: (1) build RCW foraging territories; (2) "bud" (create) RCW groups with a specified probability; (3) destroy RCW groups with a specified probability. RCW foraging territories are simultaneously built by sequentially appending adjacent cells to the territory of each RCW group until the group has accumulated sufficient foraging resources. In the event that a RCW group is unable to append sufficient unoccupied foraging cells (within the maximum RCW foraging distance of 1 km from the group's nesting cell) to accumulate the minimum required foraging resources, then that group is destroyed and its foraging cells are released for other groups. After all the territories are built, each group is sequentially evaluated for a potential bud (split) with a given probability (annual per group

bud probability is 0.1). Once a group has been selected for a potential bud, one of its foraging cells is stochastically selected (weighted by the available foraging resources) to be the nesting site for the new group, and foraging territories are simultaneously built for the existing group and the new group. If the territory build operation is unsuccessful, then only one group remains.

A typical simulation is 200 years (40 five-year RCW iterations and ten 20-year management cycles). The simulation outputs evaluated are the minimum one planning period wood volume harvested and the average number of RCW groups over the last 100 years of simulation. The former corresponds to the maximum even flow volume of timber produced, and the latter to the RCW viability, after a 100 year warming-up period.

Forest Management

The forest management cycle determines the set of stands to be harvested in the current 20-year planning period based on the user specified *management scheme*, made-up of a *RCW management policy* and an *optimization strategy*. These schemes provide the mechanism to produce different mixes of timber and RCW benefits. The *RCW management policy* defines the width of a circular buffer around each RCW group nesting cell, and the minimum harvest ages for the stands inside and outside this buffer. The reasoning here is that RCW groups can be favored by extending the harvest age for those stands nearest to the RCW nesting site. Only if the RCW proximity buffer width is assigned a value of zero can a stand with a RCW nesting group be harvested (labeled a "non-RCW management policy"). Otherwise, stands containing active nesting groups can never be harvested, although they can be scheduled for harvest in future planning periods. Information on where individual RCW groups are foraging is not used for management planning since this information is usually not available for real world management planning.

The *optimization strategy* determines whether a rule-based or a schedule-based algorithm is applied to select the stands to be harvested. The rule-based strategies programmed are volume control with random selection of stands and the selection of the oldest stands first. In either case, stands are selected for harvest until a predefined target volume is met or until there are no more stands available for harvest. The implementation of the volume control strategies requires simulations with different target volumes to determine the harvest level that results in the best combination of timber and RCW outputs.

The schedule-based optimization strategies formulate the scheduling problem as a Model I optimization problem (Johnson and Scheurman 1977) for maximizing a linear combination of the multiple objectives of minimum 1-period timber volume and accumulated RCW foraging resources. Included in the description of the optimization strategy are the relative weights assigned to the resource outputs.

These optimization problems can theoretically be solved by integer linear programming (ILP), however, for problem sizes of over 450 management prescriptions (decision variables) solutions were rarely obtained within 12 hours of CPU time with *Lindo*[3] on a SUN SPARC UNIX workstation (Hughell 1996). Because scheduling problems generated by the simulation model have up to 8,000 management prescriptions, and because each simulation run must solve 10 such optimizations (one for each 20-year management cycle), ILP is not a feasible option. Therefore, a GA optimization heuristic is utilized to produce a set of near optimal solutions in a timely manner. A GA is a random search heuristic guided by the principles of natural selection and Darwinian evolution, with its roots in efforts to model biological genetic processes through computer simulation. It is a technique for searching a space of potential solutions in order to locate a superior set of solutions which are superior (Goldberg 1989, Michalewicz 1992).

RESULTS

The RCW group behavior simulation/forest management model is applied to demonstrate the application of stochastic simulation to evaluate adaptive management schemes for the sustained production of timber and wildlife benefits. Three randomly generated landscapes and one landscape representing a 4,800 hectare section of the Croatan National Forest (eastern North Carolina) are simulated. Each random landscape is made-up of a systematic mosaic of 7-cell stands randomly assigned an age between 0 and 120 years and a site index between 45 and 105 feet (base age of 50 years). RCW groups are randomly located within the landscape. For the Croatan National Forest landscape, all pine stands are treated as longleaf pine and all non-pine stands are treated as non-forested land.

The management policies evaluated are buffer widths from 0 to 800 meters with a minimum rotation age of 100 years inside the buffer and 60 years outside. Hughell (1996) evaluated other minimum harvest ages and found these values were represented in the majority of the management schemes that make-up the joint production possibilities frontier (non-inferior solution set).

[3] *Lindo 5.3, Linear Interactive Discrete Optimizer, Lindo Systems, Chicago, IL.*

The optimization strategies evaluated are:

(i). volume control with random stand selection;
(ii). volume control with age-based stand selection;
(iii). harvest schedule (generated by GA) with weights from 0 to 1.0 assigned to timber and foraging resources.

For each management scheme (combination of management policy and optimization strategy) and landscape, eight simulation runs with identical starting conditions were executed to assess the variability in outcome. Each run covered a 200-year simulation horizon divided between 40 five-year RCW behavior cycles and ten 20 five-year management periods. The statistics collected for each run were the minimum one-period timber volume harvested (corresponding to the MAXMIN timber optimization objective) and the average number of RCW groups over the last 100 years of simulation (the first 100 years was considered a warming-up period and, therefore, ignored). These two output statistics were then averaged over the eight simulation runs for the management scheme and plotted against each other to determine graphically those schemes that define the joint production possibility frontier[2].

Management Schemes

As expected, larger buffer widths and higher weight assigned to the RCW foraging resources resulted in more RCW groups, and smaller buffers and weights produced more timber. With few exceptions, the volume control strategy with the selection of the oldest stands first was superior to the volume control strategy with the random selection of stands. This is because the older stands are usually already beyond the age where the culmination of timber volume has occurred and, therefore, are the best candidates to be harvested for the production of timber. The selection of the periodic target volume for volume control is critical to the success of the volume control optimization strategy. Here this selection is made through multiple simulation runs with different target volumes. To evaluate characteristics common to all four landscapes evaluated, the joint production possibility frontier for the simulations carried-out on these landscapes was scaled to a per hectare basis and plotted in figure 2. For all landscapes except for the largest (R200), the schedule-based optimization strategies (that define the joint production possibility frontier) produced more timber, while the non-schedule based volume control strategies produced more RCW groups. This can be attributed to the uncertainty introduced into the system by the RCW groups. With no uncertainty (i.e., non-RCW management) the GA generates a near optimal harvest schedule which, when implemented, maximizes the production of timber. However, as management objectives favor RCW groups, more uncertainty is introduced into the system and it is more likely the selected harvest schedule will become infeasible. Therefore, at some RCW density the implementation of harvest schedules becomes more of a liability than an advantage toward meeting management objectives.

With the larger landscape (R200), two factors work against the schedule-based optimization strategy. First, with more decision options (a result of the large number of stands), it is more difficult for the GA to obtain harvest schedules with a performance sufficiently near that of the optimal schedule. Therefore, management decisions are consequently based on inferior harvest schedules. The second factor is that with more stands there is more flexibility in the selection of stands to meet the target volume.

The Croatan National Forest landscape (CNF) produced less timber and fewer RCW groups per hectare (fig. 2) because of its lower overall site index (57 compared with 72 feet) and the irregular shapes of stands, making it more difficult for RCW groups to obtain a contiguous block of foraging resources.

CONCLUSIONS

Through example, this study demonstrates how optimization techniques can be coupled with wildlife behavior simulation models to test adaptive management policies and optimization strategies. However, it is important to recognize that this study is based on a highly simplified representation of reality. The behavior of RCW groups has been abstracted down to three processes: build RCW group foraging territories, split RCW groups, and destroy groups. It is assumed that timber on all stands grow along deterministic (age - volume) growth curves based only on site index. It is also assumed that the RCW foraging and nesting suitability is a deterministic function of the stand age and site index. The only stand management decision option considered is in which planning periods should a stand be harvested. As of this writing, no attempts have been made to validate the model.

Despite the simplicity of the models developed, this study demonstrates how different management policies and optimization strategies can be evaluated within the context of adaptive management. It was found that above a certain level of uncertainty, the application of non-schedule based strategies (e.g., simple volume control) are more effective at producing both superior timber and wildlife benefits than the implementation of explicit harvest schedules.

[4] *The joint production possibility frontier is the noninferior decision set of solutions, where an improvement in one of the objective is not possible without a loss in the other objective.*

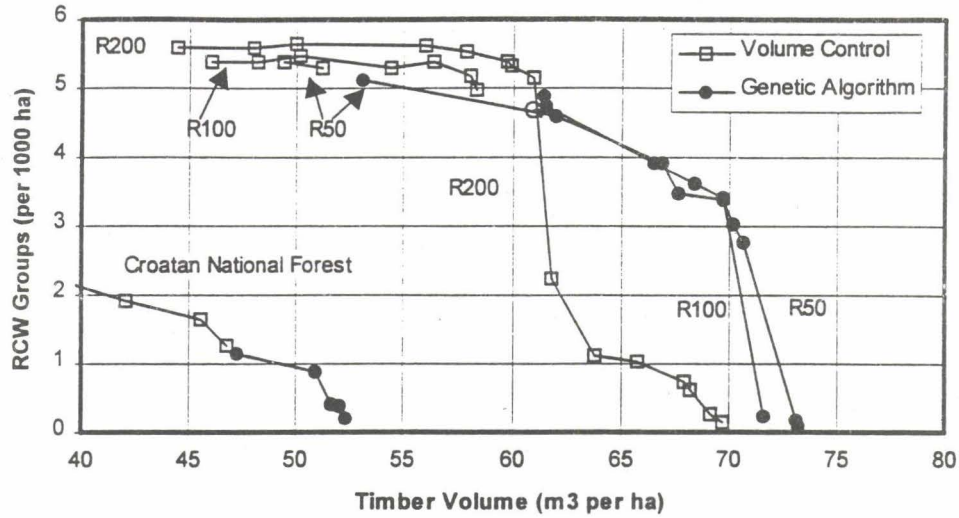

Figure 2.—*Comparison of timber and RCW outputs among four landscape studies (R50, R100, R200 and CNF). Management schemes are identified as volume control (VC) and schedule-based genetic algorithm.*

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A "GAP" ANALYSIS OF BIRD DISTRIBUTIONS IN SOUTHERN ONTARIO USING SIMULATED ANNEALING

Daniel McKenney, Lisa Venier, Ian Ball, Janice McKee, Hugh Possingham, and Brendan Mackey[1]

ABSTRACT.—In this paper we demonstrate the use of simulated annealing (an optimization technique) on large-scale field survey data to inform the design of protected area networks. We used Ontario's Breeding Bird Atlas (BBA) data because it has distribution information for 290 species during the breeding season. In southern Ontario, where landscapes have been largely transformed by agriculture and urban development, the BBA data covers 2,360 Universal Transverse Mercator (UTM) grid squares (approx. 10*10km/square). In this study we identified all species that did not occur in the major parks of the Province. We then identified the minimum number and location of UTM grid squares that would represent 5 percent of the breeding occurrences of these species in southern Ontario. There are a number of possible combinations of grid squares that meet the criteria. Four particular squares were selected in every run of the model. We visualize results in a geographic information system (GIS) to provide some insights on potential gaps in bird representation in the southern Ontario park network. We also describe implications and other possible applications.

INTRODUCTION

The government of Ontario has recently embarked on a review of its protected area network through the Lands for Life initiative (OMNR 1997). The Natural Heritage Areas Framework and Action Plan is aimed at developing a comprehensive system of parks and protected areas: "This natural heritage areas system will strive to represent the full range of natural diversity in the Province and will provide protection for other special natural heritage values important to society for their intrinsic worth" (OMNR 1996). This plan explicitly identifies one key theme as "[to conduct] the science and [identify the] methodologies needed to identify significant areas" [our interpretation]. In recent years, considerable spatial data on aspects of biodiversity have been developed in Ontario. Insights for designing protected area networks could be gained through the application of operations research techniques to much of this data. Results could be of use not only to the Ontario Ministry of Natural Resources and forest industry but also to groups like the Nature Conservancy, the Federation of Ontario Naturalists, the Canadian Wildlife Service, and other groups that have limited resources and want to more effectively focus their conservation efforts.

One purpose of protected areas or nature reserve networks is to represent and hence help to sustain biological diversity in a regional context (Margules *et al.* 1994, see also Mackey *et al.* 1989). Thus, an element of a protected area review is an assessment of how well current parks and/or reserves sample enduring landform features and the distribution of plant and animal species. The corollary of this problem is to identify locations of species that are not protected by reserves. This is not a trivial problem. For example, Canada has 3,269 species of native plants, 81 species of reptiles and amphibians, and approximately 426 bird species (Mosquin and Whiting 1992). Pinning down actual and potential distributions is challenging given the wide range of influences affecting species (e.g., climate, nutrients, species interactions, land use—see Gaston 1990 for a review).

Much has been written about both the theory and practice of designing ecological reserves (e.g., Soulé 1986). The topic is becoming increasingly mathematical (Pressey *et al.* 1997). Aside from the specific issue of designing a network of reserves, the broader issue of land allocation and management can be boiled down to problems in mathematical programming. Advantages of formulating these decisions as mathematical programming problems

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include a framework for organizing relevant data, an explicit statement of objectives and constraints, and a suite of tools for finding solutions. While considerable effort has also gone into the development of mathematical methods to help design protected area networks, they have had limited application in Canada. These methods make use of various types of environmental data (e.g., biological surveys, vegetation classifications, bioregionalizations) and range from scoring models (Bedward *et al.* 1992) and integer programming (Cocks and Baird 1989) to other types of heuristic algorithms (e.g. Lewis *et al.* 1991, Nicholls and Margules 1993, Csuti *et al.* 1997).

In this paper we demonstrate the use of simulated annealing to interrogate Ontario's Breeding Bird Atlas (BBA) data to inform the protected area planning process at a regional scale. The application has broader implications since BBA's have been developed for many states and Provinces in North America, Europe, and Australia. The specific methods used to create each atlas vary in detail but have many similarities, the most important being that they summarize the distribution of breeding of a diverse taxon over a large area. The BBA contains data on the distribution during the breeding season of all bird species known to inhabit the Province (summarized on a roughly 10*10 km basis). To demonstrate the approach, we addressed the question of what is the minimum number and locations of BBA squares that sample 5 percent of the breeding observations of all species not represented by parks in Ontario. This is just one possible question that can be addressed with these methods and data. The actual target for representativeness assessments and GAP analyses is to some extent problematic. Figures of 10 to 15 percent are commonly quoted but are subject to debate.

DATA AND METHODS

Breeding Bird Atlas of Ontario

The purpose of a bird atlas is to present the known breeding distribution of species found in the area of interest. The area of interest is usually divided into sampling grid squares. The sizes of these grid squares vary, but for Ontario they are UTM (Universal Transverse Mercator) squares of approximately 10 km x 10 km with some modifications for areas that cross UTM zones (Cadman *et al.* 1987). Grid squares were sampled for evidence of possible, probable, or confirmed breeding of all bird species. All sampling was conducted during the breeding season. In Ontario, each grid square included in the atlas had a minimum of 16 hours of sampling by volunteers between 1981 and 1985. The Atlas of the Breeding Birds of Ontario (BBA) (Cadman *et al.* 1987) represents the most comprehensive data on the distribution of breeding birds in Ontario. Ontario is a large Province (approx. 891,190 km^2) with most of the human population residing in its southern portions. There are 14,289 UTM squares in Ontario, of which 3,281 (23 percent) were sampled. We conducted our analyses only on the southern portion of the Province where the coverage was almost complete (2,109 of 2,360 possible grid squares) and habitat preservation is a more immediate concern given the extent of the transformation of its landscapes by agricultural and urban development (fig. 1). Of the approximately 290 breeding bird species in Ontario (which represent approximately 75 percent of all species breeding in Canada), between 221 and 241 species breed in southern Ontario. This area consists of three major forest regions: Boreal Forest (mainly coniferous), Great Lakes-St. Lawrence Forest (mixed forest), and Carolinian Forest (dominated by broad-leaved trees) in which very few extensively wooded areas remain due to human modification.

The question addressed here concerns species that are not represented in parks. We obtained a digital GIS coverage of major Ontario parks from the World Wildlife Fund that contains boundary information for some, but not all, of the reserves (table 1 and fig. 2). For example, there are 13 migratory species reserves in Ontario totaling 33,132 hectares that are not part of this coverage (OMNR 1996).

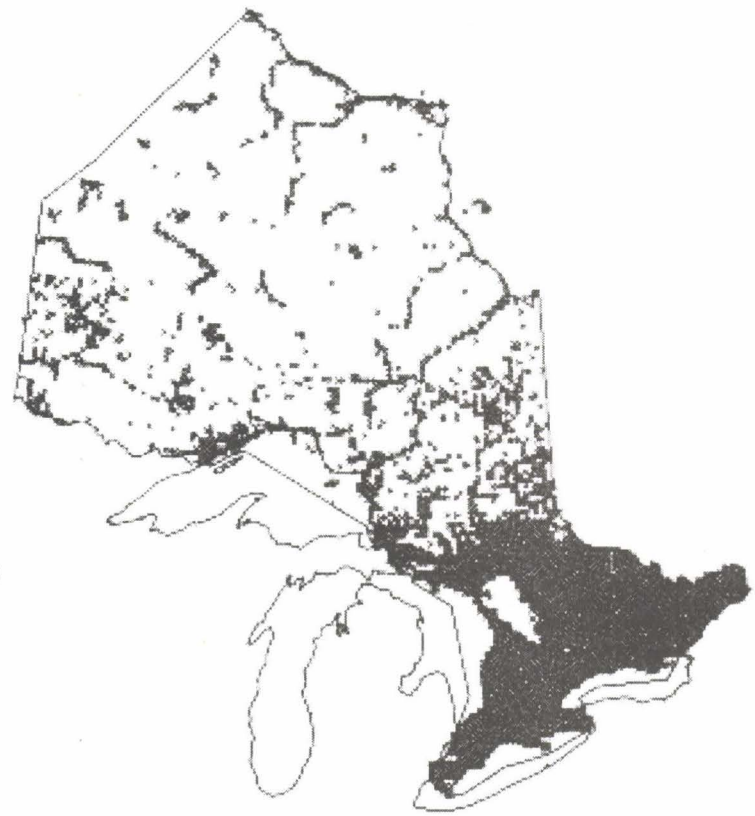

Figure 1.—*Locations of BBA survey squares in Ontario.*

Table 1.—*Provincial and national parks*

Park no. and name	Area	Park no. and name	Area	Park no. and name	Area
	km^2		km^2		km^2
1 Polar Bear	22,880.7	24 Sleeping Giant	223.0	46 Restoule	6.0
2 Winisk River	2,884.1	25 Pukaskwa	1,861.5	47 LaCloche	46.7
3 Opasquia Wilderness	4,734.3	26 Missinaibi River	531.8	48 Grundy Lake	36.8
4 Woodland Caribou	4,520.3	27 Kakabeka Falls	4.8	49 Dividing Lake	2.6
5 Kesagami Wilderness	807.4	28 Esker Lakes	34.4	50 Arrowhead	9.1
6 Wabakimi	1,676.1	29 Pie Islands	59.0	51 Killbear	12.8
7 Ojibway	23.2	30 Obatanga	91.3	52 Fathom Five	18.6
8 Winnange Lake	51.7	31 The Shoals	91.6	53 Bon Echo	55.8
9 Fushimi Lake	59.4	32 Lake Superior	1,313.2	54 Silent Lake	19.8
10 Little Abitibi	189.5	33 Michipicoten Island	184.6	55 Murphy's Point	3.9
11 Sandbar Lake	46.3	34 Lady Evelyn-Smoothwater	739.4	56 Kawartha Highlands	19.5
12 Lake Nipigon	10.4	35 Wakami Lake	89.1	57 Awenda	21.2
13 Rene Brunelle	24.7	36 Aubrey Falls	51.4	58 Frontenac	48.1
14 Nagagamisis	46.2	37 Halfway Lake	48.7	59 Charleston Lake	10.5
15 Greenwater	49.1	38 Wanapetei	33.7	60 Petroglyphs	17.2
16 Quetico	4,447.7	39 Mississagi	62.8	61 Presquile	2.6
17 Ouimet Canyon	8.1	40 Mattawa River	75.3	62 Sandbanks	18.2
18 Silver Falls	46.3	41 Samuel de Champlain	15.5	63 Bronte Creek	7.6
19 Neys	34.5	42 Mashkinonje	9.5	64 The Pinery	23.8
20 White Lake	17.4	43 Algonquin	6,331.0	65 Rondeau	19.2
21/22 Slate Islands	38.7	44 South Bay	15.1	66 Point Pelee	21.6
23 Kettle Lakes	8.5	45 Killarney	442.9		

Digital park boundaries were provided by the World Wildlife Fund and derived from the 1:2,000,000 scale National Atlas Information Service.

Figure 2.—*Boundaries of Provincial and National Parks available in digital form.*

Species that occurred in grid squares in Ontario parks were removed from the species list. Because our question related only to southern Ontario, species not found in any grid squares in southern Ontario were also removed (table 2). The final data matrix for the analysis reported here contained 46 species and 2,191 BBA grid squares. We selected the confirmed breeding data in an attempt to be conservative in identifying important areas for birds since we considered confirmed breeding more important than possible breeding.

The Simulated Annealing Analysis

Simulated annealing is an optimization technique based on an iterative improvement algorithm (Kirkpatrick *et al.* 1983). It is based on an analogy of the annealing of metals. It works by searching through the solution space looking for continual improvement of the solution, but with a large enough random element included so that it is not likely to become stuck prematurely at a local minima. The random element starts off quite large and is then reduced to zero in the same way that temperature starts out high and is reduced in annealing.

A simulated annealing algorithm was used to identify the minimum number of locations that would represent 5 percent of the species' confirmed breeding locations in southern Ontario. This is an admittedly arbitrary target but should serve to illustrate the analyses. We should note that there is no guarantee that species not included in this analysis have 5 percent of their confirmed breeding locations in the current park network. This is just a function of our initial selection criterion and could be easily modified for future analyses. The algorithm was run on the data matrix 100 times since we expected that more than one solution would be generated and were interested in investigating robustness in terms of the relative importance of UTM squares. The frequency with which a particular square is included in a solution is indicative of its importance to complete representation of the bird fauna.

The iterative improvement algorithm is itself very simple, consisting of the following steps:

1. A random selection of the UTM squares is chosen from the complete list of squares.

2. This selection receives a score. This score consists of one part, the number of squares in the system (which we wish to minimize), plus another part, the deficit in representation for species.

   In a case where we simply want to represent each species at least once, this second value is the number of species that aren't represented. When we want to represent some species more than once (as in the 5 percent problem) this second number includes a measure for each under-represented species indicating how many extra squares would be needed to represent that species. For example, if a species was seen on 95 squares in total then 5 percent representation would mean that we need at least 5 squares to adequately represent this species. If we already had 2 squares with the species on it then the penalty for that species would be 3.

3. Squares from this complete list are chosen at random to check if they should be included or excluded. If the square is part of the selection, we consider excluding it. If the square is not in the current selection, we consider including it.

4. We determine the change to the selection's score that would occur if the chosen square were either included or excluded.

5. By this formulation it is best to have as low a score as possible. Hence we accept the change if it lowers the score and reject it if it doesn't lower the score.

6. We go back to step (3) and repeat until no more changes are possible.

7. Having finished, it is possible that some species are still not represented. This occurs when the only way to include each new species is to add a square. Since we only get one new species for each added square,

Table 2.—*Species not recorded in Breeding Bird Atlas squares in Ontario parks (only parks in table 1 have been included in analysis). In parentheses (COSEWIC status[a], no. of obs., NB indicates spp. with no breeding obs. in southern region of Ontario).*

Species	Species
Horned Grebe, *Podiceps auritus* (N,3,NB)	Red-headed Woodpecker, *Melanerpes erythrocephaus* (V,729)29)29)
Red-necked Grebe, *Podiceps grisegena* (N,11)	Acadian Flycatcher, *Empidonax virescens* (E,29)
Great Egret, *Casmerodius albus* (N,20)	Carolina Wren, *Thryothorus ludovicianus* (N,39)
Cattle Egret, *Bubulcus ibis* (N,1)	Marsh Wren, *Cistothorus palustris* (N,427)
Yellow-crowned Night Heron, *Nyctanassa violacea* (N,2,NB)	Blue-gray Gnatcatcher, *Polioptila caerulea* (N,248)
Canvasback, *Aythya valisineria* (N,7)	Loggerhead Shrike, *Lanius ludovicianus* (E,145)
Redhead, *Aythya americana* (N,33)	White-eyed Vireo, *Vireo griseus* (N,19)
Rudy Duck, *Oxyura jamaicensis* (N,45)	Cerulean Warbler, *Dendroica cerulea* (V,108)
Cinnamon Teal, *Anas cyanoptera* (N,4)	Prothonotary Warbler, *Protonotaria citrea* (E,15)
Muted Swan, *Cygnus olor* (N,17)	Kirtland's Warbler, *Dendroica kirtlandii* (E,1,NB)
Golden Eagle, *Aquila chrysaetos* (N,4,NB)	Kentucky Warbler, *Oporonis formosus* (N,9,NB)
Peregrine Falcon, *Falco peregrinus* (E,3)	Blue-winged Warbler, *Vermivora pinus* (N,139, NB)
Gray Partridge, *Perdix perdix* (N,112)	Lawrence's Warbler, *Vermivora chysotera x V. pinus* (N,4)
Sharp-tailed Grouse, *Tympanuchus phasianellus* (N,54)	Brewster's Warbler, *Vermivora chrysotera x V. pinus* (N,24)
Ring-neck Pheasant, *Phasianus colchicus* (N,331)	Hooded Warbler, *Wilsonia citrina* (T,21)
Wild Turkey, *Meleagris gallopavo* (N,19)	Louisiana Waterthrush, *Seiurus motacilla* (V,40)
Northern Bobowhite, *Colinus virginianus* (E,79)	Yellow-breasted Chat, *Icteria virens* (V,45)
Piping Plover, *Charadrius melodus* (E,3)	Summer Tanager, *Piranga rubra* (N,2,NB)
Upland Sandpiper, *Bartramia longicauda* (N,709)	Dickcissel, *Spiza americana* (N,2,NB)
Wilson's Phalarope, *Phalaropus tricolor* (N,47)	Grasshopper Sparrow, *Ammodramus savannarum* (N,442)
California Gull, *Larus californicus* (N,1)	Henslow's Sparrow, *Ammodramus henslowii* (E,38)
Greater Black-backed Gull, *Larus marinus* (N,15)	Western Meadowlark, *Sturnella neglecta* (N,80)
Black Tern, *Chlidonias niger* (N,344)	Orchard Oriole, *Icterus spurius* (N,113)
Yellow-billed Cuckoo, *Coccyzus americanus* (N,352)	House Finch, *Carpodacus mexicanus* (N,187)
Eastern Screech Owl, *Otus asio* (N,617)	Purple Gallinule, *Porphyrula martinica* (N,2,NB)
Northern Hawk Owl, *Surnia ulula* (N,9,NB)	Mountain Bluebird, *Sialia currucoides* (N,1)
Common Barn Owl, *Tyto alba* (V,6)	Yellow-headed Blackbird, *Xanthocephalus xanthocephalus* (N,14)
Chuck-will's-widow, *Caprimulgus carolinensis* (N,6)	
Red-bellied Woodpecker, *Melanerpes carolinus* (N,115)	

[a] COSEWIC (Committee on the Status of Endangered Wildlife in Canada) status: N = no status, E = endangered, T = threatened, V = vulnerable.

the score isn't lowered and the change isn't accepted. This is a desirable conclusion because it can often leave us with a suite of possible selections that represent each species all being of equal value.

The algorithm can be described more precisely as follows:

Starting with the cost system,

$$c = \sum_{i=1}^{m} x_i + p \sum_{j=1}^{n} STEP(\sum_{i=1}^{m} a_{ij} x_i)$$

where

$$STEP(x) = \begin{cases} 1 & x > 0 \\ 0 & x \leq 0 \end{cases}$$

c is the cost that we wish to minimize, and x_i are the states of the site vector $\boldsymbol{X}$ (1 if site i is included in the system and 0 otherwise). The penalty scalar (p) for not representing a bird, is typically set to either 1, or even 1.001 to make the representation of a bird worth slightly more than one site. The elements a_{ij} in matrix $\boldsymbol{A}$ are set to 1 if bird j has been seen in site I, and 0 otherwise.

The cost function for the 5 percent problem is a variation on this one with a more complicated method to determine the penalty, analogous to the one above, for not representing a bird.

1. Randomly choose an initial reserve system **X** and set initial 'temperature' $T = T_0$ and 'temperature length' $\boldsymbol{L}$ (an integer).

2. Select a site I at random.

3. Calculate Δc, the change in the value of c if the state of x_i were to change, i.e., from 1 to 0 or from 0 to 1.

4. If $\Delta c < T$ (the change criteria) then change the state of x_i.

5. Repeat steps 2 to 4 L times.

6. Reduce T and increase L by the appropriate factor. Go to 5. This is repeated until $T = 0$ after which the process terminates.

The resultant vector $\boldsymbol{X}$ is the solution.

This is just one realization of iterative improvement, but it is the one that fits in nicely with simulated annealing. The problem of iterative improvement algorithms is that they could get 'stuck' in a local minima rather than the global one. This would occur where changing any one square might not lead to an improvement but by changing two or more simultaneously you could get an improvement. Simulated annealing is a method that can decrease the chance of getting stuck in any local minima by allowing some moves that do not improve the value of the solution. The probability of bad moves decreases as the annealing process continues so that the final moves are all improvements (Otten and van Ginneken 1989).

The main subtlety in the simulated annealing technique is determining an appropriate annealing schedule. The type of annealing schedule determines how long the algorithm needs to run in order to produce valuable results. In our implementation, we have used a simplified negative exponential function as the basis for annealing. Although this increases the number of repetitions needed, it simplifies computation.

RESULTS AND DISCUSSION

Seventy bird species were not found in the UTM squares sampled by the entire Ontario park network. Eleven of these species did not have any observations in the south and were eliminated. Ten more species did not have any breeding observations in the south and were also eliminated from the analyses (table 2). Thirteen of the remaining species are listed as threatened, endangered, or vulnerable by the Canadian Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and hence are considered to be of particular concern (Cook and Muir 1984).

In 100 runs, the mean number of grid squares required to sample 5 percent of the breeding distribution of all 46 species was 29. As noted, given the nature of simulated annealing, there is some variation in the number and configuration of grid squares in the final solutions. More than 50 percent of the grid squares were selected 1 or 2 times in the 20 solutions reported in figure 3. These grid squares are the least critical or the most easily replaced by other UTM locations. Four locations were selected in all of these 20 runs. These sites have been selected because they seem to represent four particular species: Cinnamon Teal (*Anas cyanoptera*), Mountain Bluebird (*Sialia currucoides*), California Gull (*Larus californicus*), and Peregrine Falcon (*Falco peregrinus*). The first three of these are actually outside of their normal range (i.e., western species) so their appearance in Ontario could be considered as not very important (an anomaly). The Peregrine Falcon does not breed in Ontario any more except where it has been introduced. The BBA data is out of date in this regard. These results highlight the need for judicious species selection in this type of analysis. Bird species could be further filtered to include only those for which Ontario has a "conservation responsibility" (Cheskey 1995).

One advantage of an approach that generates multiple solutions is that more options or choices can be illustrated for decision makers. The fact that there are

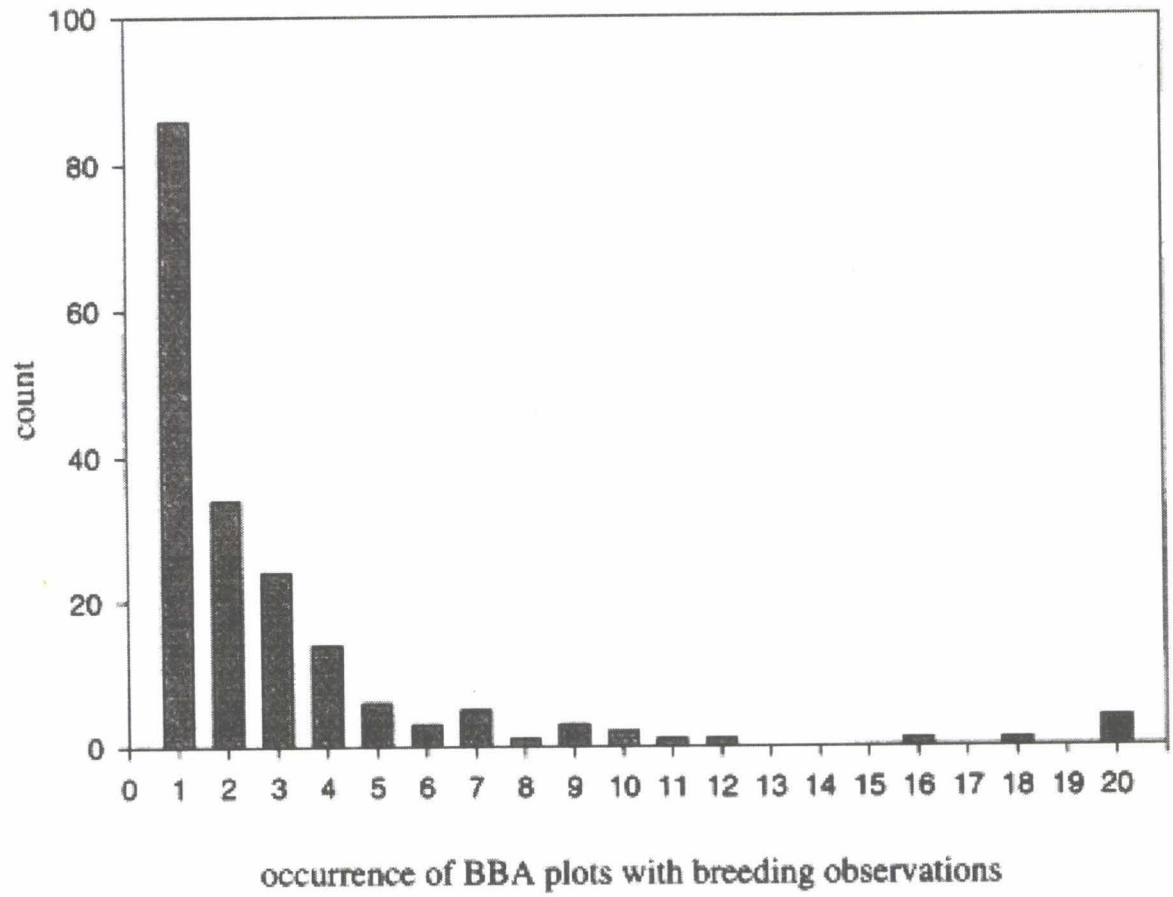

Figure 3.—*Frequency histogram of the occurrence of BBA plots with breeding observations in 20 simulated annealing runs.*

alternative solutions also demonstrates some flexibility in the approach. However, as the problem is articulated in a more sophisticated manner (e.g., criteria involving minimum distance from roads, contiguity), the number of choices would likely decrease because fewer sites would meet the specified criteria.

A map of the locations for one simulated annealing run shows no concentration of the selected UTM squares in any particular area, although many of the selected sites (14) occur along shorelines, areas more likely to offer high habitat diversity (fig. 4). Some sites were more frequently included in solutions than others; the most critical squares are those that occur in the most solutions. For this simulation, there are no selected UTM squares in the vicinity of Algonquin Park (#43 in fig. 2), the largest forested park in the study region. While this may seem counterintuitive to those familiar with Ontario birds, most of the species that do occur in this area are likely found in Algonquin Park and would therefore not be included in the analysis. In addition, forest dwelling species would likely be represented in the northern park network (albeit not necessarily 5 percent of their distributions).

CONCLUDING COMMENTS

There is currently a review of the reserve network in Ontario. Methods and data are required to assess the effectiveness of current reserve network in representing Ontario's natural heritage. Formulating the reserve design problem as a mathematical programming problem and solving it using simulated annealing (or any other operations research method) has the advantage of providing a framework to organize relevant data and of making objectives explicit. Simulated annealing is one method well suited to large problems like the one presented here. BBA data provide a lot of information about the distribution of all bird species that occur in the Province. The analyses reported here identified areas of the Province that are not part of the current reserve network but that seem to be important for representing breeding locations. These particular locations could be considered for monitoring and/or conservation programs. For example, these may be areas that could be protected or where incentives could be given to landholders to reduce their use of pesticides or other bird-unfriendly activities.

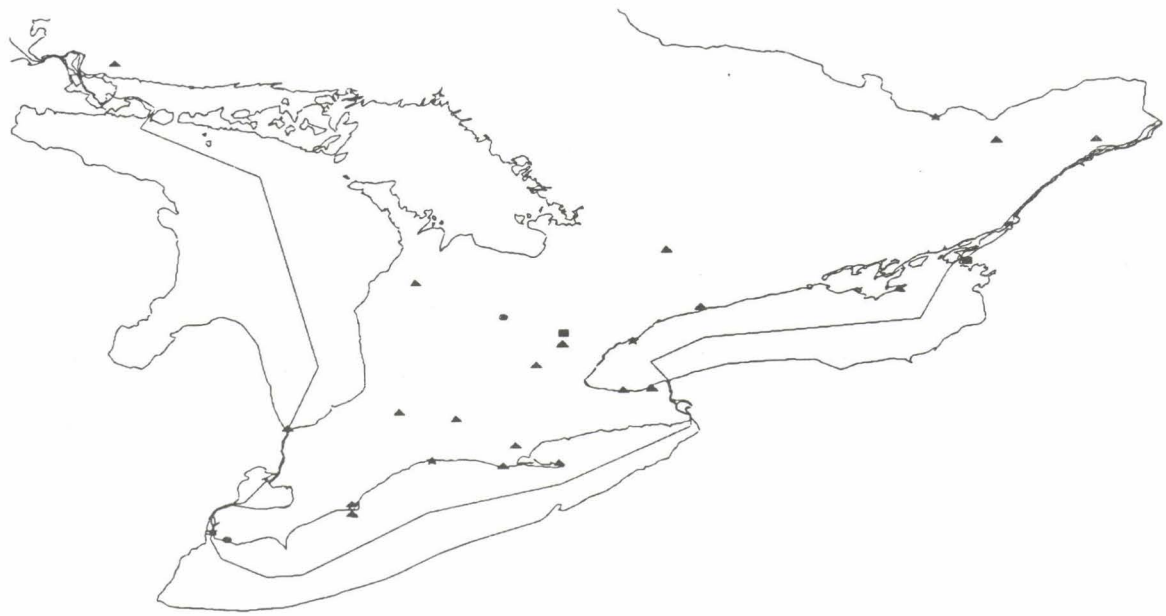

Figure 4.—*Breeding BBA locations selected in one simulated annealing.*

We have presented an example of the sort of problem that needs to be addressed to review protected area networks. Some of the information necessary for a comprehensive Ontario analysis is still being developed, including a complete digital coverage of current protected areas. Also, specific questions could be more refined. For example, schemes to establish priority species are now under development (Cheskey 1995). The "importance" of species could then be incorporated into this type of analysis.

More importantly, the methods are not restricted to BBA data, this scale of analysis, or this particular problem configuration. For example, the methods we used could be applied at a scale more familiar to those working in forest operations. Consider a problem in which a forest manager wants to maintain a specified level of habitat for some large number of species. Spatially explicit habitat maps are being developed in Ontario and elsewhere by linking vegetation cover (e.g., Forest Resource Inventory) data to species life history information. At this scale, the spatial configuration (e.g., adjacency considerations) of habitat could be more critical. In principle, such analyses could also identify important locations in a manner that minimizes the impact on other land uses.

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CARBON STORAGE, INCOME, AND HABITAT DIVERSITY IN MANAGED TROPICAL FORESTS

Marco Boscolo and Joseph Buongiorno[1]

ABSTRACT.—A recurrent theme in the tropical forestry literature is the need to manage tropical forests for multiple uses. To improve our ability to quantify the economic tradeoffs between income from timber production and other environmental services, we developed an optimization model for the management of a lowland dipterocarp forest stand in Peninsular Malaysia. Forest productivity and environmental performance were quantified by a growth model calibrated using a dataset from the Pasoh forest. This study presents some results of optimal cutting policies for a forest stand in a steady state. Economic (NPV) and ecological criteria were considered such as habitat diversity and carbon storage. To maintain minimum levels of carbon storage or habitat diversity caused significant reductions in NPV. Tradeoffs are accomplished by lengthening the felling cycle and by modifying the cutting regime.

INTRODUCTION

Managers and policymakers are increasingly recognizing that tropical forests provide various commodities and environmental services of global value. For example, tropical forests play an important role as carbon sinks and harbor an extreme diversity of life, both of perceived interest to the global community (de Montalembert 1991). Such recognition has fueled a search for ways to manage tropical forests sustainably and for multiple uses (e.g., Peters *et al.* 1989, Panayotou and Ashton 1992).

However, while the need to account for sustainability and multiple values in forestry decisions is widely recognized, its implications for forest management are not clear. What are the characteristics of sustainable forest use? How should current management schemes be modified to consider nontimber values? Answering these questions is important, for example, in the design of policy instruments that can achieve given levels of environmental protection and in the evaluation of their feasibility and cost-effectiveness.

To address these issues we developed an economic model to quantify the effect of nontimber goods (carbon storage and habitat diversity) on the optimal cutting policy in the management of a lowland tropical rain forest in Peninsular Malaysia. Our objective was to extend and complement previous models by explicitly recognizing the effect of logging damage and by considering both carbon storage and biodiversity. Logging damage was modeled explicitly because, in dipterocarp forests, it strongly affects the structure of the unharvested portion of the forest stand (cf. Appanah and Weinland 1990) and is, therefore, an important determinant of forest productivity. Carbon storage and biodiversity were considered simultaneously to highlight the differences, and similarities, of their effects on tropical forest management.

The purpose of this paper is to briefly summarize the features of this model and to present some results obtained by optimization analyses. Analyses were carried out with reference to steady state scenarios. This approach was chosen to obtain results that are independent from initial conditions, while embodying the principle of sustainability. In fact, in a steady state, the forest stand yields the same flow of benefits at each cycle, in perpetuity. It also provides valuable information for policymaking which often compares the desirability of "equilibrium" or "sustained yield" states.

THE MODEL

The model adopted for this study is an extension of the transition matrix model developed originally by Buongiorno and Michie (1980). Boscolo *et al.* (1997) modified it to allow for multiple-species (similarly to Buongiorno *et al.* 1995, and Ingram and Buongiorno 1996). In this model, transition probabilities (growth and

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mortality parameters) depend on species group and tree size. Ingrowth depends on species composition and stand density. The model was calibrated with data from a 50-hectare, demographic plot located in Peninsular Malaysia and predicts the evolution of a forest stand with trees grouped in 3 species cohorts (dipterocarps, commercial non-dipterocarps, and noncommercial) and seven size classes. Model parameterization and calibration are described in Boscolo *et al.* (1997). The effect of harvesting on stand structure and composition included consideration of logging damage, which we assumed as proportional to the timber volume extracted. The effect of logging on the residual stand was based on data obtained from the literature (e.g., Appanah and Weinland 1990, Pinard *et al.* 1995).

MANAGEMENT CRITERIA

The desirability of alternative steady states was judged by two ecological criteria (mean carbon storage and deviation from the climax state) and by an economic criterion (Net Present Value).

The first ecological criterion considered was the amount of carbon stored in the living tree biomass. At any given point in time, the carbon storage depends on the forest state, which itself depends on the growing stock before logging, the intensity of the last cut, and the time interval since that cut. In a steady-state regime, the amount of carbon in the stand, before harvest, is the same at the beginning and at the end of the cutting cycle. The carbon stored increases steadily as the stand grows between harvests. To account for this variation, the *mean carbon storage* (MCS) was chosen as a measure of the sink capacity of a representative stand in steady-state[2]. Mean carbon storage over a cutting cycle is:

$$(1) \quad MCS = \sum_{l=t}^{t+p} K_l/(p+1),$$

where K_l is the carbon stock at the end of year l. One ecological goal would be to keep MCS as high as possible.

A second ecological criterion (DEV) measured the distance between a given stand and its climax state, and was defined as:

$$(2) \quad DEV = \max (DEV_{ij}),$$

with $DEV_{ij} = (B^*_{i,j} - B_{i,j}) / B^*_{i,j}$, where $B^*_{i,j}$ is the basal area of trees of species i and size j in the climax forest, while $B_{i,j}$ is the basal area in the managed stand after the cut. Thus, according to this criterion, the structure and composition of the climax forest is set as the most desirable state. Moreover, of alternative sustainable stand states, the one closest to the climax state is deemed preferable.

For management purposes, one ecological goal would be to keep DEV, the maximum deviation (among all species and size classes) from the climax distribution, as small as possible. The effect of this mini-max criterion is to give special attention to the tree category that is least represented and that, in a managed stand, will deviate the most from that observed in natural climax stands. It is the analog to the maxi-min diversity criterion of Buongiorno *et al.* (1995), and both are consistent with the concept of a "safe minimum standard of conservation" (Ciriacy-Wantrup 1968).

The Net Present Value (NPV) was considered as the economic criterion, given by the present value of future timber revenues, net of all costs (including the cost of the investment in the growing stock). Thus, in a steady state, the economic harvest and the growing stock should be chosen so that the maximum NPV is attained. To discount future revenues, the interest rate was set to 6 percent per year, the return (net of inflation) of alternative investment opportunities in Malaysia (Ingram and Buongiorno 1996).

A COMPARISON OF ALTERNATIVE STEADY STATES

Optimization of either ecological criterion (i.e., max MCS or min DEV) led to a solution almost identical to the climax state. In this solution, the stand would store 214 tons/ha with a basal area of 25 m^2/ha. Therefore, in absence of other constraints, maximization of either ecological criterion was attained by complete preservation at a cost, in terms of NPV, of $4,240/ha.

Maximization of the economic criterion led to a solution where all commercially valuable trees (dipterocarps and commercial dipterocarps with dbh ≥ 30 cm) would be cut every 20 years. This solution attained a NPV of $702/ha while MCS dropped to 168 tons/ha. At the same time, the maximum deviation from the climax state rose to 100 percent (at least one tree category is completely felled).

To assess the effects of ecological considerations on the optimal economic cutting policy, a minimum carbon storage and a maximum deviation constraint were imposed. Through parametric variations of the minimum acceptable level of carbon storage (or maximum tolerable level of deviation in the case of the tree distribution criterion), we derived alternative steady states and measured their economic and ecological performance.

[2] *As noted elsewhere (see, for example, Stavins 1996 and Boscolo* et al. *1997) there exist other carbon accounting procedures. Summarizing carbon flows in an index such as MCS treats equally carbon flows in the near and distant future.*

Storing more carbon required decreasing the harvest while increasing the felling cycle. For example, to attain a MCS of 200 tons/ha, the annual harvest would have to be lowered from 0.85 m^3/ha (obtained through unconstrained NPV maximization) to 0.24 m^3/ha and the felling cycle increased from 20 to 55 years. At the same time, the NPV would fall to -$1,767/ha (table 1).

Similar results were obtained when NPV maximization was constrained by a minimum deviation of the tree distribution from the climax state. To keep basal area in any species-size class within at least 50 percent of that in a virgin stand would require an annual harvest of 0.42 m^3/ha and a felling cycle of 30 years. The NPV would fall to -$1,730/ha (table 2).

As it can be seen by comparing tables 1 and 2, the two ecological criteria led to different cutting regimes. To attain a MCS of 200 tons/ha, only dipterocarp trees with dbh ≤ 60 cm would have to be cut (table 1). Some tree categories would have to be harvested completely. Therefore, according to our tree distribution criterion, we would still record a 100 percent maximum deviation from the climax state. On the other hand, to maintain a tree distribution at least 50 percent of that in a primary stand would require a light tree selection in all commercial classes. This solution would improve the tree distribution criterion together with MCS, which would increase from 168 to 191 tons/ha.

DISCUSSION AND PRELIMINARY CONCLUSIONS

Using a model calibrated with data from a 50-hectare demographic plot in Peninsular Malaysia, we explored the features of steady states characterized by different combinations of management criteria. Applications were presented with respect to economic (NPV) and ecological criteria: mean carbon storage and deviation from the climax state.

To improve either ecological criterion caused a significant reduction in terms of NPV. This trade-off would be accomplished by a progressive lengthening of the felling cycle and by modifications of the cutting regime. The main difference between the carbon storage and tree distribution constraints is in the resulting optimal harvests. A MCS between 168 and 195 tons/ha, for example, would require all dipterocarp trees with dbh > 30 cm to be cut. Thus, this criterion implied the total elimination of at least one tree category. Instead, a tree distribution closer to the climax state would be obtained with a light tree selection in all commercial classes which would also attain some increase of MCS. This result

Table 1.—*Steady state that maximized soil rent while keeping mean carbon storage at 200 tons/ha*

Diameter class	Dipterocarps		Comm. non-dipterocarps		Noncommercial	
	Number of trees/ha	Cut	Number of trees/ha	Cut	Number of trees/ha	Cut
cm						
10-20	30.1	0.0	74.4	0.0	2,75.2	0.0
20-30	11.5	0.0	21.6	0.0	65.2	0.0
30-40	5.3	4.7	10.9	0.0	20.3	0.0
40-50	3.5	3.5	5.7	0.0	7.5	0.0
50-60	2.4	2.4	3.8	0.0	3.0	0.0
60-70	1.2	0.0	2.1	0.0	1.0	0.0
70+	1.8	0.0	1.9	0.0	1.0	0.0

Felling cycle:	55 years
Total number of trees (before cut):	549 trees/ha
Total number of trees (after cut):	497 trees/ha
Basal area (before cut):	23.7 m^2/ha
Basal area (after cut):	21.4 m^2/ha
Residual stand damaged:	7.7 %
Extracted volume:	0.24 m^3/ha/yr
Harvest revenues (net):	$413/ha
Present value of harvests:	$17/ha
Value of residual stock:	$1,785/ha
Net Present Value:	-$1,767/ha
Mean Carbon Storage:	200 tons/ha
Maximum deviation of all tree categories:	100%

Table 2.—*Steady state that maximizes soil rent while deviating by less than 50 percent from the tree distribution in the climax state*

Diameter class	Dipterocarps		Comm. non-dipterocarps		Non-commercial	
	Number of trees/ha	Cut	Number of trees/ha	Cut	Number of trees/ha	Cut
cm						
10-20	35.0	0.0	68.1	0.0	276.8	0.0
20-30	13.2	0.0	19.3	0.0	64.5	0.0
30-40	5.8	3.1	8.4	3.9	20.1	0.0
40-50	3.6	1.6	3.4	1.1	7.5	0.0
50-60	2.5	0.7	1.8	0.2	3.0	0.0
60-70	1.5	0.2	0.9	0.0	1.0	0.0
70+	3.0	0.1	0.8	0.0	1.0	0.0

Felling cycle:	30 years
Total number of trees (before cut):	541 trees/ha
Total number of trees (after cut):	490 trees/ha
Basal area (before cut):	22.3 m^2/ha
Basal area (after cut):	20.2 m^2/ha
Residual stand damaged:	7.5%
Extracted volume:	0.42 m^3/ha/yr
Harvest revenues (net):	$228/ha
Present value of harvests:	$228/ha
Value of residual stock:	$1,778/ha
Net Present Value:	-$1,730/ha
Mean Carbon Storage:	191 tons/ha
Maximum deviation of all tree categories:	50%

suggests that the goal to maintain some diversity will also generate some co-benefit in terms of increased carbon storage while the opposite will not necessarily be true.

The analyses also suggest that the high timber value of Malaysian lowland dipterocarp forests translates into a high cost of maintaining carbon storage and habitat diversity. In other words, the modification of cutting policies such as felling cycles or cutting prescriptions is an expensive strategy to protect the above non-timber values. These results are consistent with the findings of Boscolo *et al.* (1997), who used the growth model to simulate future harvest revenues and variations in the carbon stock when logging a virgin forest stand. Their results are summarized in figure 1, where each point corresponds to a particular combination of felling cycles, diameter cutting limit, and logging technology. In particular, the diagram displays the combinations of the control variables that were Pareto efficient (i.e., where one output, carbon or harvest revenues, could not be improved without diminishing the other).

It should be noted that their economic and carbon storage indicators differed from the ones used for the steady state analyses. With respect to carbon, for example, carbon flows were used instead of mean storage[3]. Furthermore, variations of carbon storage over time were discounted as if carbon had a market price. These differences impair a direct comparison of results between the simulation and the optimization analyses. Notwithstanding these differences, figure 1 indicates that significant carbon savings can be attained at a relatively low cost in terms of present value of harvest revenues. Thus, the shift from conventional to reduced-impact logging methods could be a more cost-effective way to achieve carbon savings than imposing restrictions on cutting practices.

[3] *In our steady state analysis, it did not make much sense to compute carbon flows since a fixed initial reference point did not exist. In fact, in our steady state analysis, the stand initial conditions were generated as part of the optimal solution. Thus, we replaced carbon flows by mean storage, perhaps a simpler and more intuitive concept as well.*

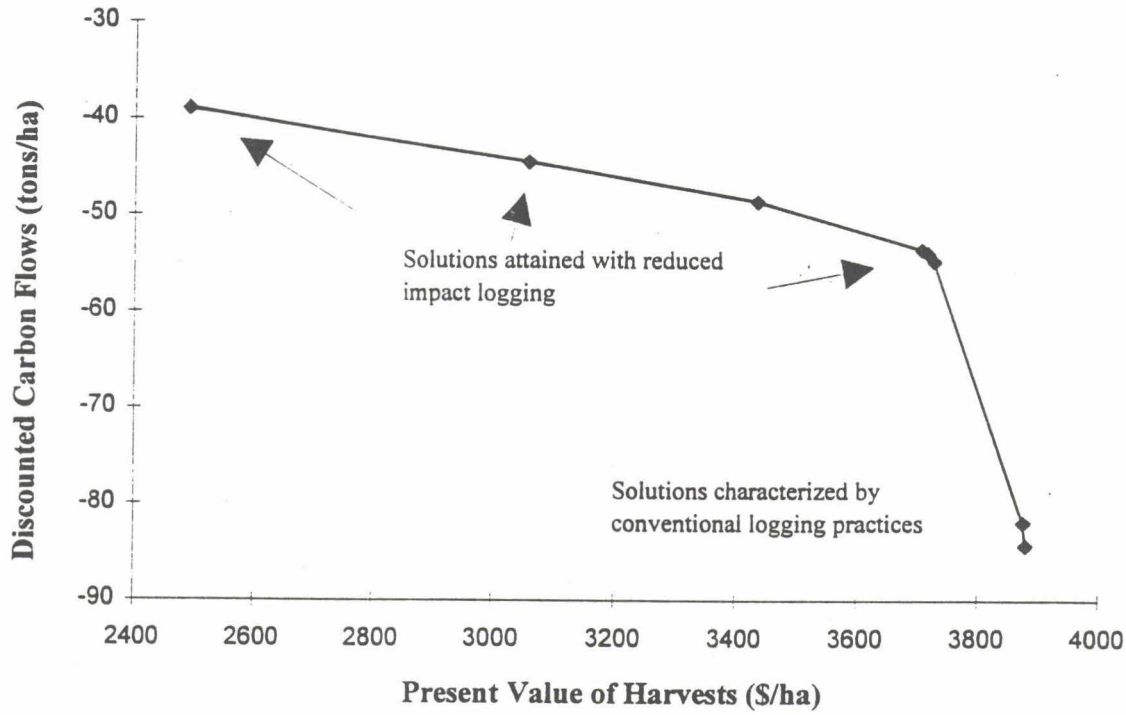

Figure 1.—*Tradeoff curve between present value of harvests and discounted carbon flows (Source: adapted from Boscolo* et al. *1997).*

This appears to be true, at least, when logging a virgin stand, since more trees of large dimensions are extracted and, therefore, more damage is caused to the residual stand. In a managed forest, on the other hand, fewer and smaller trees are extracted[4] and a lower level of damage is caused (tables 1 and 2). Additional research is needed to assess the ecological and economic benefits and costs of modifying logging technology in logged-over stands.

Finally, quantification of the economic tradeoffs between economic and ecological criteria in tropical forestry remains an important area of research as is the study of which policy instruments will yield environmental protection at the least cost. These are some of the themes on which our current research is focused.

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[4] *Unless, of course, different species are harvested or felling limits are modified at each cut.*

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EXAMINING THE ROLE OF MARKET MECHANISMS IN AMELIORATING DEFORESTATION

Ashok K. Saxena, Jagdish C. Nautiyal, and David K. Foot[1]

INTRODUCTION

The impact of natural resource scarcity on economic growth has often been debated in the context of developed nations (Hotelling 1931, Meadows *et al.* 1972, Dasgupta and Heal 1979, Houthakker 1983, Baumol 1986, Bower 1987, Cleveland 1991). In recent years, the issue of resource scarcity has received renewed importance in the economic and environmental planning of developing nations (Meadows *et al.* 1992, World Bank 1993, Hyde *et al.* 1996). There are three prominent views in this debate: classical, neoclassical, and biophysical.

The classical economists such as Marshall and Ricardo argued that fixity in the supply of arable land and a declining land quality, when combined with an expansion in production, will eventually constrain economic growth. In their view, natural resource scarcity will ultimately negatively impact economic growth.

The neoclassical economists (e.g., Dasgupta and Heal 1979, Houthakker 1983, Baumol 1986, Bower 1987), however, challenged the classical paradigm and suggested that the means of escaping from increasing scarcity lies in the market mechanism. According to this view, natural resource scarcity will sow the seeds of its own amelioration, since the scarcity of resources will eventually trigger price increases which, in turn, will reduce demand and stimulate a host of resource-augmenting processes. These processes include substitution of alternative resources, increased efficiency in use of resources, increased exploration for new reserves, recycling, and technical innovations in resource exploration, extraction, processing, and transformation. In summary, the neoclassical school argues for the efficacy of market mechanisms in ameliorating scarcity. If the resource markets are working according to the precepts of the neoclassical school, resources are being allocated efficiently over time, and no policy intervention is required. For example, in a perfect market, the scarcity caused by deforestation would result in appropriate price signals that would in turn bring about investments in the forestry and other sectors (Hyde *et al.* 1996) and a reduction in the demand for forest products. These price signals would result in increased production from forests and a new economic equilibrium where the supply and demand for forests would balance each other.

Biophysical analysts view the relation between resource scarcity and its process of amelioration differently. These scholars argue that basic physical and ecological laws constrain our economic choices and are not correctly reflected in the economic models and market price signals (Ayres and Nair 1984, Cleveland *et al.* 1984, Hall and Hall 1984, Daly and Cobb 1989, Cleveland 1991). These authors, therefore, advocate strong policy initiatives to ameliorate resource scarcity. The biophysical analysts emphasize that there are massive, yet unmeasured, throughout transfers from the environment to the economy; that is, massive quantities of natural resources are poured into the resource-harvesting process, substituting in an unmeasured way for reductions in capital and labor use. These resources are not adequately accounted for in the traditional market mechanisms and economic measures (Cleveland 1991). For example, the forestry sector in India is measured to contribute less than 2 percent of measured gross national product (GNP) (World Bank 1993). This is because much forest produce does not go through markets (Dwivedi 1994). Further, this figure does not take into account the numerous nonmarket benefits (oils, medicinal plants, silk, resins, dyes, fibers, and leaves) or the vast amounts of fuelwood, fodder, and industrial timber removed for personal use and trade that are not traded through formal markets. It also ignores environmental service benefits of forests not only to India but also to the rest of the world (Woodwell 1992, World Bank 1993).

Besides the absence of markets, there are situations where markets fail, especially in forestry. First, the well known existence of externalities occur in the forest process (Mahar 1990, Rowe *et al.* 1992, Woodwell 1992). Deforestation depletes forest stock, which in turn impairs the watershed functions of forests. However, this loss may not be recorded in the market system. Second, because of the externality cost associated with

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forest use, there is a divergence between the private and social costs of nonforest land uses and commercial timber harvesting, and the market fails to appropriately guide these decisions. Third, because forests produce several goods and services, the problem of valuing joint products and nonmarket environmental services further limits the efficacy of market solutions. Moreover, the conflict between the time horizon of people now living and the needs of future generations creates a bias in favor of exploiting forests now versus conserving for the future. Finally, undefined—or poorly defined—and poorly implemented property rights create open access to forests and retard successful forestry investments. All of these failures weaken the operation of the market system (Rowe *et al.* 1992). Accordingly, in addition to market linkages, it is essential to understand the biophysical links that drive the deforestation process.

This paper suggests that all three views—classical, neoclassical, and biophysical—have their merits. Therefore, it is important to incorporate the linkages reflecting all the views in a system approach to any environmental problem such as deforestation. Since a system incorporates several linkages, these linkages may act as negative and positive feedback mechanisms. Inherently, the arguments of the neoclassical writers focus on strong negative feedback. Increasing scarcity results in price increases that ultimately result in decreasing scarcity. However, the success of the relationships between scarcity and the processes that may ameliorate the scarcity will depend on the strength and speed of the various responses. Accordingly, focusing exclusively on one set of linkages may lead to incorrect results and mislead the resource policy planners. Because the strength and speed of these relationships will vary from location to location and from time to time, the merit of various solutions for ameliorating resource scarcity will vary depending upon the location and time of the problem. A system dynamics approach can capture these effects.

The case for a multifaceted approach is particularly convincing in developing economies where markets and market mechanisms in the forestry sector may not be well developed or widespread in their use and impacts. In developing countries, especially for those facing deforestation and forest biomass scarcity, either markets for forestry resources generally do not exist or, if they do exist, are not fully developed. As a result, the market mechanisms may not be significantly useful in influencing the dynamics of the forest sector.

This paper presents a system framework that incorporates the linkages suggested by the economic perspective, including the efficacy of market mechanisms, and those suggested by the biophysical perspective, highlighting the significance of extractive biophysical linkages. It then analyzes the role of the market in the amelioration of deforestation. Based on data for India, the paper shows that the set of plausible relationships that the neoclassical school has assumed in the efficacy of the market mechanisms to ameliorate forest biomass scarcity are not effective in developing countries. There is an urgent need to supplement the market process by strong policy initiatives if forests are to be conserved. The understanding of the biophysical linkages may help in determining the needed policy initiatives for amelioration of deforestation especially in developing countries.

METHODOLOGY

A systems model is constructed wherein the forest sector interacts with four other sectors: the agriculture, livestock, socioeconomic, and energy sectors that compete for forest land or forest produce. The process of deforestation is modeled in terms of dynamic interrelationships within and among these sectors. The relationships are specified through mathematical equations. The authors used Stella, a simulation language (see High Performance Systems 1994), to build the five-sector model pictured in figure 1.

The efficacy of market mechanisms in ameliorating deforestation is examined on two levels. First, the authors examined the theoretical validity of price linkages in alleviating forest biomass scarcity, particularly in the context of developing nations. Second, the price linkages are modeled and the two systems profiles are compared: the profile illustrating only the biophysical linkages, and the profile incorporating both the biophysical and price linkages in the system. The first level of examination offers an opportunity to analyze if markets function in the forestry sector of developing countries in general, and in India in particular. The second level of analysis will assist in discerning the impacts of market mechanisms on the dynamic profiles of key forestry stocks, and hence, their effectiveness in preventing increasing scarcity of forest resources.

EXAMINING THE ROLE OF PRICE

The role of price in arresting deforestation is examined in two steps. In the first step, the authors introduce various linkages in the suggested relationships between scarcity and price signal responses as negative feedback relationships. Their relevance to a developing country in general and to India in particular is evaluated. In the second step, the causative chain of connections between increasing prices and increasing removal representing the positive feedback relationships are discussed and introduced to represent the total effect of price increases on biomass scarcity. This examination demonstrates that

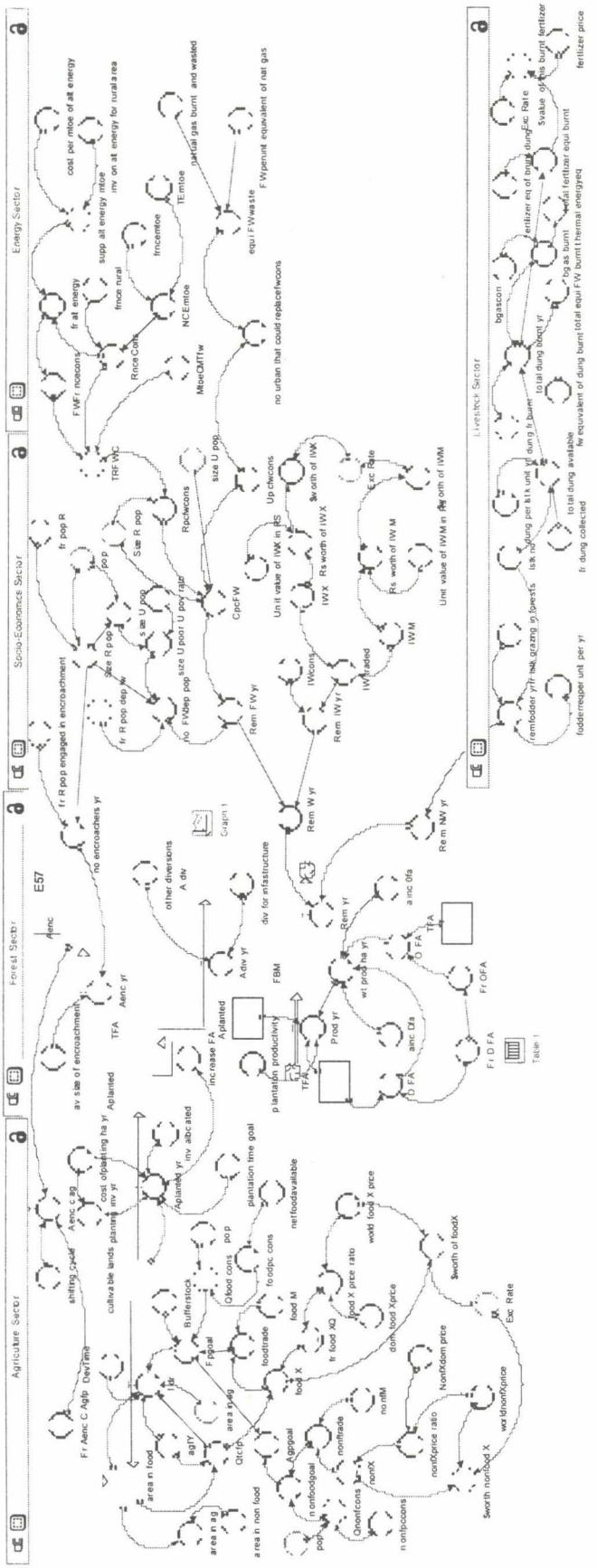

Figure 1.—*A five-sector model of deforestation.*

the outcome of the effect of price on deforestation will depend upon the speed and strength of the various responses that connect scarcity and price increases.

Negative Feedbacks

The relationship between forest biomass scarcity and the rise in prices seems to be clear. However, to make this relationship operational, various assumptions must be made. The various linkages assumed to make the relationship operational are represented in figure 2.

As the process of deforestation progresses, it depletes forest biomass. The resulting scarcity is theoretically accompanied by the rise in price that decreases demand and attracts entrepreneurs to invest and to make profits from the rising prices. The increased investment flow eventually results in an increase in the production of forest biomass, and in turn reduces the scarcity of forest biomass. The reduction in scarcity abates further price increases. Thus, the relationships between deforestation and biomass scarcity result in price and investment increases along with demand decreases, which bring about an increase in supply of forest biomass which acts to slow the original process of forest depletion. These relationships represent two negative feedback loops. Upon closer scrutiny, one observes that the operation of the negative feedback supply loop hinges on the operation of four linkages between these variables. The first is between deforestation and biomass scarcity, the second between the forest biomass scarcity and price increases, the third between price increases and increases in investment flow, and the fourth between investment flow increases and the increase in biomass production. Unfortunately, all four of these linkages are almost non-operational in developing countries in general and in particular in India.

In addition to the supply response to the forest biomass scarcity, there is a theoretical demand response that suggests a reduction in the consumption of forest biomass due to increase in price of forest biomass. However, the demand response is weakened by the fact that much forest biomass removal is not traded through markets. In India, 90 percent of the forest biomass removed is for fuelwood, but the removal is not recorded in the markets. The fuelwood is generally consumed by the poor (Dwivedi 1994). These people do not have income to purchase alternative forms of fuel but obtain fuelwood for free as a forest "right" or by illegally removing from the public forests. Fuelwood demand substitution is weak in a poor society and, especially for the poor people, the fuelwood demand response seems to be inelastic to price response (Mercer and Soussan 1992). Rising income rather than prices has been observed as the predominant factor in fuelwood substitution (Barnes 1986). The substitution of fuelwood is further weakened by the unavailability of alternative fuels such as kerosene, especially in the rural areas, and the availability of fuelwood at relatively low or no cost. Thus, the two main forces that drive the fuelwood substitution are access to dependable supplies of alternative fuels and income (Mercer and Soussan 1992). Unfortunately in most developing countries, and particularly in India, both forces are weak.

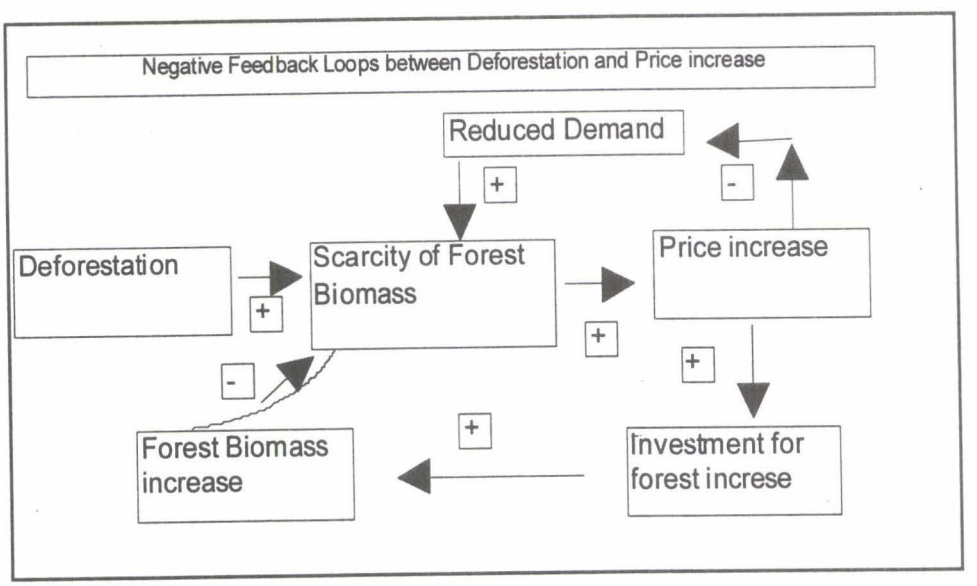

Figure 2.—*Illustration of negative feedback loops between scarcity and price.*

Linkage Between Deforestation and Biomass Scarcity

In developing countries, particularly in the case of India, the positive relationship between the progression of deforestation and forest biomass scarcity is well established (World Bank 1993). However, it is possible to visualize a scenario where deforestation may be progressing but the scarcity of biomass is not perceived or measured. There are four main reasons why such a scenario is possible. First, the very nature of forests having a long gestation period results in a need for a very large inventory to produce output on a regular basis. With a very large inventory, it is difficult to perceive scarcity when the inventory is being used up. For example, in Canada, large forest areas have been logged but have not been fully replanted (either by natural or artificial regeneration), and forest diversions (for infrastructure needs) have not been fully compensated. The deforestation problem is not perceived primarily because Canada has a very large inventory. In Canada, the average forest area per capita is very high (14.2 ha per person). Second, many forest goods and services may not enter markets, and thus do not have observable prices. Therefore, the markets do not record the depletion of inventory. In addition, although the inventory may be low, the market may not see the depletion of inventory because of government ownership and bureaucratic apathy. A significant percentage of unrecorded removals theoretically suppress the price signals in such a way that depletion of the inventory and the true physical scarcity are not reflected in the markets. For example, in India a significant percentage—about 80 percent—of fuelwood and fodder removals are unrecorded. The recorded fuelwood production is 40 million cubic meters, while the estimated fuelwood consumption is 235 million cubic meters. The gap between production and consumption clearly highlights a significant percentage of unrecorded removals. Inventory may be low and the goods may be physically scarce, but so long as the inventory exists and is being used up, goods may not turn into market scarce goods.

Finally, although forest biomass scarcity clearly exists in India, it is not perceived at a national scale because it does not hurt those who make the decisions at the national level. India does not import fuelwood or fodder and hardly ever imports industrial wood. Rather, until the 1980s, it exported more wood products than it imported (Government of India 1987). Scarcity is perceived at a local scale and mostly hurts the poor and vulnerable groups of the society, especially women and children (Agrawal 1986). These groups do not have purchasing power to influence the market or sufficient time and institutions to challenge the decision-making process at national or regional levels. Nor can they direct investment allocations to address their pressing problems. Ironically, even if the planners know the problems facing the local population, the influence, interests, and "wisdom" of the elite usually prevail. For example, investment allocations in the energy sectors in India do not address the energy problems of the rural and urban poor. Allocations are skewed in favor of the needs of tiny powerful sections of elite who are the politicians, bureaucrats, industrialists, and zamindars (Reddy and Prasad 1977). Consequently, there are both economic and political reasons that explain the weak linkages between deforestation and perception of forest biomass scarcity.

Linkage Between Forest Biomass Scarcity and Price

The second linkage assumes that forest biomass scarcity is transmitted to the market; that is, that the increased demand tends to push up the average prices in the forest biomass market. However, it is important to note that increased scarcity does not transmit instantaneously and automatically to the market. The delay in transmission may lead to the complete destruction of forestry resources in a locality. In that event, the forestry resources of the neighboring locality are used. In many cases, there are increases in the resource prices, but in most of these cases the increases in prices just reflect the cost of transportation and not the cost of irreversible damages that might have occurred due to depletion. Furthermore, it is the intervening element—"income spent"—that translates physical scarcity into market scarcity, and in turn triggers the market mechanism. Unfortunately, in most of the developing world, and especially in India, the poor are primary consumers of forest biomass, but do not have income. However, income is required to purchase goods from the market. In the absence of employment and income-generating opportunities, it is much more economically efficient for the poor people to invest their own time and travel farther to gather fuelwood and fodder than to spend money on purchasing them. The poor substitute their time, which they do have, for income, which they do not have. In economic parlance, this substitution of time for income occurs because the expected opportunity cost of time invested is less than the expected economic gain from fuelwood or fodder gathering. Under this scenario, the increased scarcity does not push up the prices; instead, it translates into an increase of time investment in the collection of fuelwood and fodder. The increased scarcity therefore increases the hardships faced by the poor. Their physical exhaustion further impoverishes them by reducing the time they might have for education, skill development, and the search for gainful employment. Thus, increased scarcity does not automatically translate into price increases, but rather into increased physical stress, further forest biomass depletion, and in turn, decreases in the opportunities for human development. As a result, many poor people find a lucrative job opportunity in illegally removing the forest biomass, especially fuelwood and industrial wood. A survey of 170 households in nine

villages in Bihar showed (fuelwood) head-loading served as a major source of income for one-fifth of the households (World Bank 1993). After satisfying their needs, they sell a fraction of the fuelwood to adjoining towns or cities at prices much below the cost of tree-raising plantations, which continues to exacerbate forest biomass depletion and scarcity. Thus, the market, in absence of appropriate management institutions and equitable socioeconomic conditions, instead of providing a solution to the deforestation problem, is facilitating deforestation. Furthermore, this discussion points out a need to extend the linkage between scarcity and price. This could probably be done by providing gainful income-generating opportunities so as to increase the opportunity cost of time while reinforcing it by stiffening the penalties associated with illegal removal of forest biomass.

Linkage Between Price and Investment Flow

In a market economy, the price signals will direct the investment flow to maximize the allocative efficiency of investment. However, in most developing countries price signals do not respond to scarcity. Even if it is assumed that the price signal responds to scarcity, the investment flow to the afforestation activity does not correspond with the price increases; that is, the linkage between the price rise and investment flow may be weak or broken. This is especially true when the scarce resource is owned by the public sector and the hypothesized private sector responses are replaced by public institutions. The current allocation of investment by the planning commission and regional governments is neither related to the biomass scarcity nor to the price increases. The allocations may not be purely arbitrary, but they definitely are not market driven.

Indeed, the strength of the linkage between the price rise and investment flow depends on the ownership pattern of a resource, and the time preferences of the resource owners. For example, about 90 percent of the forests in India are publicly owned, and the time preference of governments that are elected only for 5 years is generally high. These governments give priority to investments with short gestation periods and emphasis on the short-term economic achievements. Obviously, the public investment in forestry, which itself has a long gestation period, does not attract much public funds because of strong political reasons and weak financial justification.

In India, forests do not seem to be important to financial planners, as the accounted contribution of forests to the financial flows is low. The forestry sector contributes less than 2 percent to measured GNP. Public investment is low and is not related to forest biomass scarcity (World Bank 1993). Investment for afforestation was 0.39 percent of the total public sector outlay in the First Five Year Plan. It varied from 0.46 percent to 0.63 percent of total public outlay from the Second to Fifth Five Year plans. It rose to 0.71 percent in the Sixth Five Year Plan to a little over 1 percent in the Seventh and dropped to 0.95 percent again in the Eighth (Dwivedi 1994). Outlays to forestry were less than 1 percent of the total public sector outlay between 1951 and 1995, although the price index of timber increased from 100 in 1970-1971 to 2,398 in 1992-1993 (Saxena 1994). In summary, the linkages between price rises and investment flows are weak in India. This is also true for other industrializing nations such as Bangladesh, Nepal, Pakistan, and Sri Lanka.

Linkage Between Investment Flow and Forest Biomass Flow

The assumption that increased investment flow will also increase forest biomass flow and seems to be working in industrializing countries only in a very restricted manner (World Bank 1993, Chaturvedi 1994). Perhaps the limited success can be attributed to the fact that the linkage carries with it two more assumptions to make it work. The first assumption is that the investments are successful; that is, that the afforestation activities result in successful plantations. The second assumption is that the plantations will survive until maturity to provide the increased forest biomass. However, it is observed that only 41 percent of the plantations are successful in India (Chaturvedi 1994). The remainder either die because of natural plantation mortality (this includes transplantation shock, adverse soil and temperature conditions, and diseases) or are consumed because of heavy grazing pressures. Further, if they survive the first few years of establishment, they are prone to removal or damage by fuelwood collectors before maturity (World Bank 1993). The gestation period between the investment flow and forest biomass outflow is long and is full of uncertainty. As a result, there is no immediate increase in forest biomass, even after an increase in the investment flows in the forestry sector.

It is during the plantation maturation period that the positive feedback loops work speedily and forcefully, while the negative feedback loop remains dormant. Therefore, the relationships between increased scarcity, price increases, demand decreases, investment increases, forest biomass supply increases, and reductions in scarcity as envisioned by neoclassical economic theory operate in a very limited way or do not operate in most developing countries. There is a need to extend the conventional Neoclassical theoretical argument of negative feedback loops by incorporating the other positive relationships emanating from the scarcity and price rises of forest biomass.

Positive Feedbacks

As noted above, forest biomass scarcity generates another set of pressures on the forest biomass: the pressures of illegal removals. As deforestation continues, the forest biomass scarcity increases, and the average price increases at local levels. While the returns on illegal forest removal increase, the risks involved in forest offenses do not correspondingly increase. For example, in the state of Rajasthan, one truckload of teak (approximately 8 m^3) has an illegal market value of $4,000 while the maximum punishment, if apprehended and found guilty, is $400. Even, if the probability of being caught is 50 percent, it is economically rational and lucrative to illegally remove teak from the forests since the expected returns are much higher than the expected costs. This scenario is true for many locations. Therefore, with the rise in prices of forest biomass, the illegal trade kicks in at an accelerated pace. This increases the amount of forest biomass removed illegally and dampens the rise in prices in the legal market, which thus acts as a disincentive to private forest investors. The World Bank (1993) observed that output from private fuelwood plantations cannot compete with the illegally removed fuelwood supply. Therefore, private plantations fail to be a rational economic proposition in the context of developing countries in general, and particularly in India. The other adverse effect of illegal forest biomass removal is that it usually degrades the forests, increasing deforestation and, consequently, the forest biomass scarcity further.

Moreover, the salaries of India's forest protection staff are low, yet they are asked to control a "high return-low risk" illegal activity at considerable personal risk. There is no link between expected benefits (wages) and the increased expected costs, so there is no incentive to increase policing. In addition, to minimize the personal risk, it is tempting to become involved in this economically rewarding illegal activity. The result is that collusion with offenders becomes an economically rational activity, and deforestation continues.

Figure 3 incorporates the other positive, as well as negative, loops that are operational in the forestry sectors of a developing nation in addition to the often emphasized negative feedback loop (the relationships between the scarcity and market mechanisms that tend to decrease demand and increase investments to counteract the increasing scarcity). The positive loops include the relationships between the increasing scarcity of forest biomass resource, the changing (here, increasing) return-to-risk ratio in illegal removal of forest biomass, increasing degradation of forests, and the increasing scarcity. The additional negative loop is the relationships between increasing scarcity and increasing resource price, increasing resource price and increasing tendency to illegally remove, which in turn triggers the chain of relationships: given demand increasing supply of the resource, depresses the price of the resource, and in turn, diminishes the profitability and tendency to invest for augmenting the resource.

In summary, the market mechanism is not singly confined to the often argued and emphasized negative price loops but may extend into various other positive and negative relationships. Therefore, the role of markets will be determined by the interaction of more than one relationship. The market institution may reduce or aggravate the scarcity depending upon the strength and

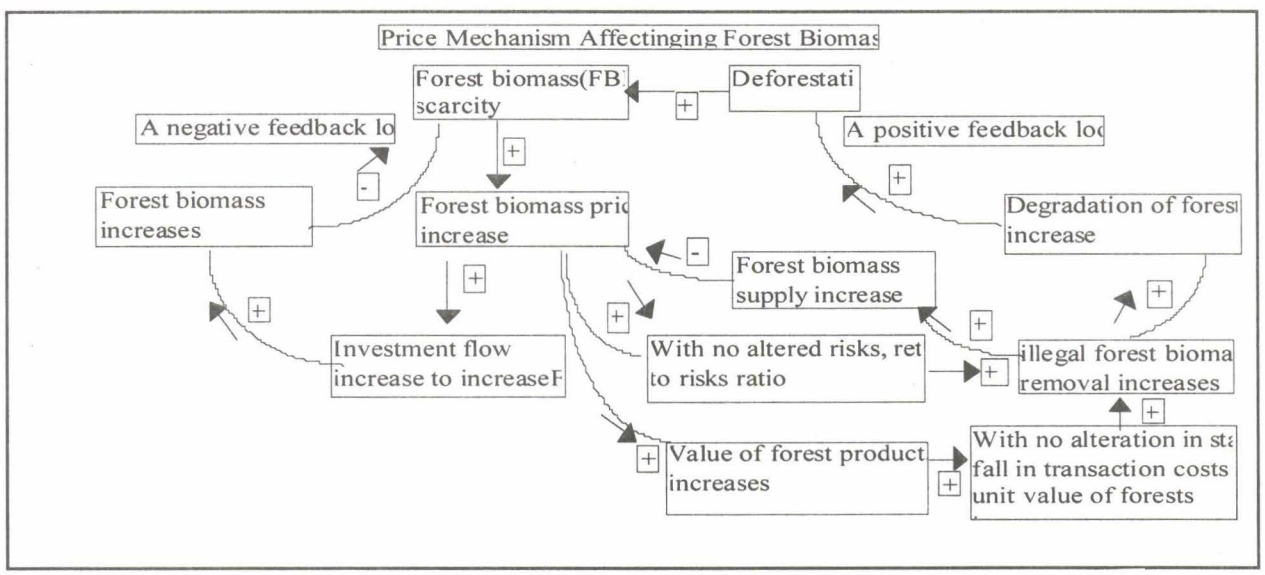

Figure 3.—*Illustration of negative and positive feedback loops between scarcity and price.*

speed of various relationships that emanate from the relationships between scarcity of resource and the price increases of the resource in the context of developing countries, particularly in the case of India. The next part of the analysis can be seen in Saxena and Nautiyal (1997).

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TOWARDS INTERGENERATIONAL EQUITY IN LP BASED LONG TERM FOREST PLANNING MODELS

Roger Church and Peter J. Daugherty[1]

ABSTRACT.—Standard linear programming (LP) formulations of forest planning problems are not explicit enough in their treatment of time to address intergenerational equity (IE) concerns. A modified model, which includes present net worth (PNW) accounting rows from the perspective of future planners, is presented. These accounting rows are used to evaluate solutions from each planner's perspective. When these PNWs are used in a MAXMIN formulation, the model solution represents a form of intergenerational Rawlsian equity between planners, where the minimum PNW outcome is maximized.

INTRODUCTION

Intergenerational equity (IE) is a simple notion. Any one generation does not want to leave a future generation relatively worse off. IE requires a human concern for the future of the young or yet-to-be born human beings that will populate the planet. However, it is one thing to accept IE as a relevant goal for society and something else entirely to actually do something about it. The difficulty lies in defining what constitutes equity between generations, and, just as importantly, what this definition implies for the current generation. Forestry as a profession has been and continues to be concerned with future generations. This concern is evidenced by such concepts as long-term sustained yield (LTSY), and by such tools as long-term forest planning models. In this paper we argue that while linear programming (LP)-based long-term forest planning models include a time dimension and long-term timber supply constraints, the models do not explicitly address IE. The case for this claim is made in the first part of the paper, which includes interpretations of IE. The body of the paper investigates an initial approach for explicitly including IE in forest planning models. This initial approach is based on modifications of a traditional forest planning model formulation. We took this approach to answer the question of how to move from existing forest planning models towards models that can better address notions of IE. The intent at this time is not to re-define the problem, but to move current approaches in a meaningful direction with respect to IE.

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INTERPRETATIONS OF EQUITY AND INTERGENERATIONAL EQUITY

Equity addresses relative distribution. Within the current generation, equity involves the relative distribution of resources, rights, and wealth amongst people (Young 1992). The neoclassical economic approaches to within generation equity focus on Pareto optimality. The intent is to find an aggregation of individual utilities that represent social welfare while avoiding interpersonal comparison of welfare. Since no such aggregation has been developed outside a perfect market, neoclassical economics continues to rely on the Pareto optimality concept, using the compensation principle (Young 1992). Pareto optimality describes an allocation of resources such that no other allocation would make at least one person better off and no one else worse off. When evaluating changes in allocation (e.g., public projects), one cannot determine if the reallocation is a Pareto improvement without evaluating the distributional changes and effects on individual utility (Scitovsky 1941). The compensation principle is an extension of Pareto optimality that attempts to avoid the difficulty with individual utility comparison by defining a potential Pareto improvement. Decisions or reallocations are a potential Pareto improvement if the gainers could compensate the losers such that no one is worse off (Kaldor 1939). Decisions are allowed under this criterion even if no compensation is required (Young 1992). By attempting to avoid distributional issues and individual utility comparisons, the potential Pareto improvement criterion fails to address equity. Mathematical decision models based on marginal analysis implicitly rely on the potential Pareto improvement criterion. When used for public planning, these models also fail to explicitly address distributional issues and within generation equity.

Addressing within generation equity requires qualitative interpersonal comparison of utility or preference. Rawls (1971) proposed a standard for equity based on people collectively allocating resources prior to knowing what share they would receive. The application of this standard results in the raising of the worse-off allocation to some minimum level. Intergenerational, or between generation, equity adds the dimension of time to equity consideration. IE addresses issues of equity between people from different time periods. The addition of time greatly influences equity and what it constitutes. The Rawlsian standard becomes more difficult to apply because future generations cannot sit at the current allocation table. The Rawlsian standard has been interpreted to mean leaving the next generation the same total level of conditionally renewable resource stocks. The limitation of this standard is that it requires assumptions about future generations' preferences for resources, which are most often assumed to be the same as the current generation's preference. We believe that IE is best addressed by evaluating options passed to the next generation, so that they can use the options to solve their own problems. This approach follows Brown-Weiss (1990), who examined IE from a policymaking perspective. She proposed a criterion of value independence between generations. A policy principle should not require one generation to predict the preferences of other generations. This criterion leads directly to one of her policy principles, the conservation of options. In this principle, each generation should conserve the diversity of the resource base so as to provide the flexibility to future generations to solve their own problems and make their own decisions. Under this approach IE addresses the relative distribution of options between generations. The issue of predicting preferences is avoided because one could evaluate decisions on the cardinality of options passed on, rather than on the value of the options. The problem becomes defining what constitutes an option.

Naturally, the definition of options is where things become complicated. For example, in forest planning models, how do we define the set of options to use in evaluating equity? In this paper we will leave the question of options unaddressed. Instead we will consider how to modify current planning models to include a Rawlsian standard. The modifications entail a more explicit consideration of time in forest planning models. The approach will still rely on the assumption that future generations will retain our preference ordering. We will use existing variables of the model as criteria for considering Rawlsian equity.

LP-BASED FOREST PLANNING MODELS AND TIME

The occurrence of future economic events is typically handled by discounting (Young 1992). All future values are discounted to present-day values using a given interest rate. However, discounting can discriminate against the interests of future generations by emphasizing the value of present day activities over those that may occur in the future (Young 1992). Discounting reduces time to a common denominator, rather than explicitly considering different time periods. Norgaard (1991) argues that it is inappropriate to use discounting to allocate resources through time. Discounting should be used to evaluate the efficiency of capital, and IE allocation should be addressed through explicit assignments of resource rights through time.

Since the mid-1970's, the USDA Forest Service has been required to include some form of efficiency analysis in forest planning. LP models have been prevalent, starting with FORPLAN Version 1 and continuing to the latest LP model generator, Spectrum (USDA Forest Service 1997). These models are used to optimize land allocation and schedule the occurrence of activities and outputs over time (USDA Forest Service 1997). The models use discrete time periods to represent the passage of time, and decision variables are indexed by the period in which they occur. Discounting of future costs and returns is common in such models, and the models often maximize present net worth (PNW). The needs of future generations are commonly addressed through harvest flow and LTSY constraints. These constraints can be viewed as the assignment of resource rights to future periods. Each period has the right to the same level of timber harvest, and no period may harvest more than the long-term sustainable level.

While these LP-based forest planning models include notions of equity between time periods, they are solved from the perspective of the current planner, and use discounting as a tool for allocating over time. The perspectives of future planners are not explicitly included in the formulations. The models are solved as closed loop systems, with a focus on the current time period over future periods. Although we assign the rights to the same harvest level to future periods, we allow the current planner to optimize the allocation from the current generation's utility (i.e., maximizing PNW). A more explicit consideration of the future planner's perspective would better address IE concerns in forest planning models. The allocation of harvest rights over time should be based on the perspectives of future planners, as well as the current planner's perspective. This notion is the basis for our approaches to modeling the forest planning problem.

APPROACHES TO MODELING

Three approaches to modeling were used to generate outcomes for comparison. All approaches included the

addition of accounting rows that represented the perspective of future planners. In a standard formulation, a planner would maximize the PNW of a schedule of activities over time, with the current (first) planning period viewed as time zero. Likewise, planners in subsequent periods would also be expected to do the same thing. From their perspective, their period would be the current period and activities from earlier periods would not count towards their PNW. Accounting rows were added to a standard 20-period forest planning model formulation to calculate the PNW from the perspective of the first 10 period planners. PNW was calculated for the activities of 10 periods, starting with the period viewed as current by each planner. For example, the accounting row for the planner in period 1 would calculate the PNW of activities from periods 1 through 10. The row for the planner in period 2 would calculate the PNW of activities from periods 2 through 11, with all values discounted as though period 2 were period 1.

Each of the three approaches used different objective functions to vary the perspective from which the model was solved. The first approach (MAXPNW) followed the standard approach of maximizing PNW over the 20 periods of the planning horizon from the first period planner perspective. The accounting rows represent the solution's PNW from the perspective of the first 10 planners, if they followed the solutions schedule of activities. Next, the PNW from each planner's perspective was maximized. These outcomes represented the maximum outcome for each planner, if they controlled all activities, both past and present. These 10 model runs constituted the second approach to modeling (MAXPLANNER). The third approach to modeling (MAXMIN) used a modified maxmin formulation, which maximized the minimum PNW for the set of planners. From an equity viewpoint, the third approach represents a form of Rawlsian equity between planners, in which the worst outcome for the set of 10 planners is raised. Each planners' PNW was also included in the objective function to allow individual planner's PNW to exceed the minimum. Weighting ensured that the minimum PNW was maximized first. The formulation was:

Maximize:

$$(1) \quad 100\, PNWMIN + \sum_{i=1}^{10} PNWPLANNER_i$$

Subject to:

$$(2) \quad PNWPLANNER_i - PNWMIN \geq 0; \ \forall i,\ i = 1, \ldots, 10$$

$$(3) \quad PNWPLANNER_i = \sum_{t=i}^{i+9} (Revenue - Cost)_t / (1+r)^{10(t-i)+5}; \ \forall i,\ i = 1, \ldots, 10$$

Where: $PNWMIN$ = the minimum of the present net worths from each planner's perspective; $PNWPLANNER_i$ = the present net worths from each planner's perspective; and r = the discount rate.

It should be noted that a true approach to maximizing the minimum would be an iterative process, with an objective function that just maximized the minimum PNW. Following each run, the minimum PNW from the run would be used as an absolute constraint for those planners whose PNW was at the minimum. The model would then be solved again, in order to raise the minimum PNW for the remaining planners. This process would continue until the minimum PNW could no longer be raised. We used the above formulation so that only one model run would be required, allowing such a change to be easily incorporated into current models.

The three approaches were run on three sets of initial conditions. Initial conditions were varied because they affect what the current generation can leave to future generations. Given the focus of this approach on the PNW from each planner's perspective, we used these PNW as the criteria for evaluating the equity of the three approaches. These criteria do not address the notion of options, and therefore do not fully address IE concerns. However, these criteria are easily developed and are relevant when comparing standard formulations of the forest planning problem to other formulations.

THE BASIC MODEL

In developing the model for this evaluation, we chose to create a simple hypothetical model for ease in applying the approaches outlined above, and especially in varying the initial conditions. The LP model was created using the SARA (Spreadsheet Assisted Resource Analysis) system (Scott 1991). An Australian forest example was chosen for variety. The timber yield information, based on a clear-felling system, was obtained from West and Mattay (1993), and the economic information from McKenney (1990). The single tree species used was *Eucalyptus regnans (F.Muell)*, or Mountain ash. The model had 20 10-year periods. The land types were 14 age classes of Mountain ash, from 0-10 years old through 130+ years old. Harvesting was not an option for age classes less than 50-60 years old. The primary output of the model was saw log volume, which had yields by age class and revenue specified per unit volume. A fixed cost per hectare harvested was employed. The model included a nondeclining yield constraint for saw log volume, along with a constraint that the final period saw log volume must be less than or equal to LTSY. Ten accounting rows were included in the model, to represent the PNW of 10 periods of activities, from the perspective of the first 10 planners. In addition, an accounting row for

the PNW of all activities over the 20 periods, from the first planner's perspective, was included. Twelve runs of the model were required for each set of initial conditions, one to maximize the PNW over all 20 periods, 10 to maximize each planner's PNW, and 1 for the MAXMIN formulation. The initial hectares in each age class were varied to model 3 initial conditions, EVEN, YOUNG, and OLD, each with a total of 14,000 hectares. These conditions are presented in table 1.

The EVEN initial condition represented a balanced forest structure with equal areas in all 14 age classes. The YOUNG and OLD initial conditions represented skewed forest structures with the majority of hectares at either end of the age class distribution.

MODELING RESULTS

The MAXPLANNER approach resulted in PNW's for each planner that were roughly equal to the first period planner's PNW. All planners could obtain a PNW comparable to the first period planner's PNW if they could control the allocation. Future planners restricted harvest in earlier periods to enable them to maximize PNW from their perspective. Results from this approach are not presented in detail. The remaining results refer to the MAXPNW and MAXMIN approaches. The saw log volume harvested per period showed little variation by approach or by initial condition. In the MAXPNW approach, volume harvested was at the maximum allowed by the LTSY constraint in every period, for all the initial conditions. For the MAXMIN approach, virtually all periods were at the maximum allowed, those that were not were at 98 percent or higher of the maximum.

The PNW's from each planner's perspective for the MAXPNW and MAXMIN approaches are presented in figures 1, 2, and 3 for each of the initial conditions. The MAXPNW approach represents the standard approach of maximizing the PNW over the planning horizon. For all three initial conditions, this approach led to the first period planner receiving the highest PNW, with subsequent planners receiving a lower PNW. The EVEN (fig. 1) and OLD (fig. 2) initial conditions exhibited a declining PNW for all subsequent planners. This decline in PNW occurred even though harvest volume was non-declining. In the YOUNG (fig. 3) initial condition, PNW declined rapidly for the first six planners and then rose for the last four, although not to the level obtained by the first period planner. The PNW's from the MAXMIN approach showed a more uniform distribution than the MAXPNW approach. For all three initial conditions, the PNW's for early period planners are lowered to allow the raising of the later period planner's PNW. Under the EVEN initial conditions (fig. 1), the first eight planners PNW's are lowered to benefit the last two planners, with the greatest decrease occurring in period one. In the OLD initial condition (fig. 2) the PNW's of the first nine planners are lowered to benefit planner 10, resulting in an even-flow pattern of PNW. In the YOUNG initial condition, the first three planners' PNW is lowered for the benefit of planners four through seven.

The hectares harvested by period for the MAXPNW and MAXMIN approaches are presented in figures 4, 5, and 6. The hectares harvested do not vary by approach for the first five periods for the EVEN initial condition (fig. 4), for the first seven periods for the OLD initial condition (fig. 5), and for the first two periods for the YOUNG initial condition (fig. 6). All three initial conditions exhibit a similar pattern in regard to the first peak in amount of hectares harvested. The MAXMIN approach shifts the first peak in hectares harvested to earlier periods, relative to the MAXPNW approach.

Table 1.—*Initial conditions, in hectares, by age class*

Condition	Age Class													
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130+
EVEN	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
YOUNG	1867	1733	1600	1467	1333	1200	1067	933	800	667	533	400	267	133
OLD	133	267	400	533	667	800	933	1067	1200	1333	1467	1600	1733	1867

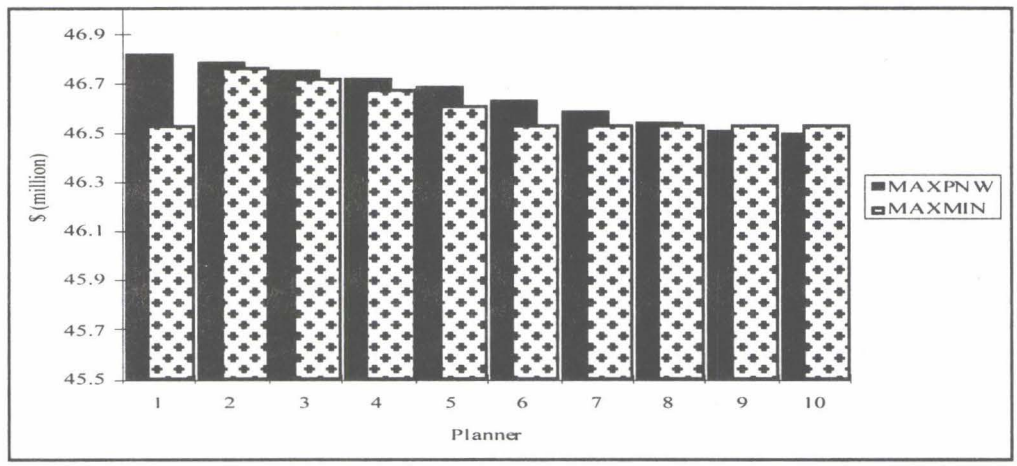

Figure 1.—*Comparison of PNW by Planner—EVEN initial condition.*

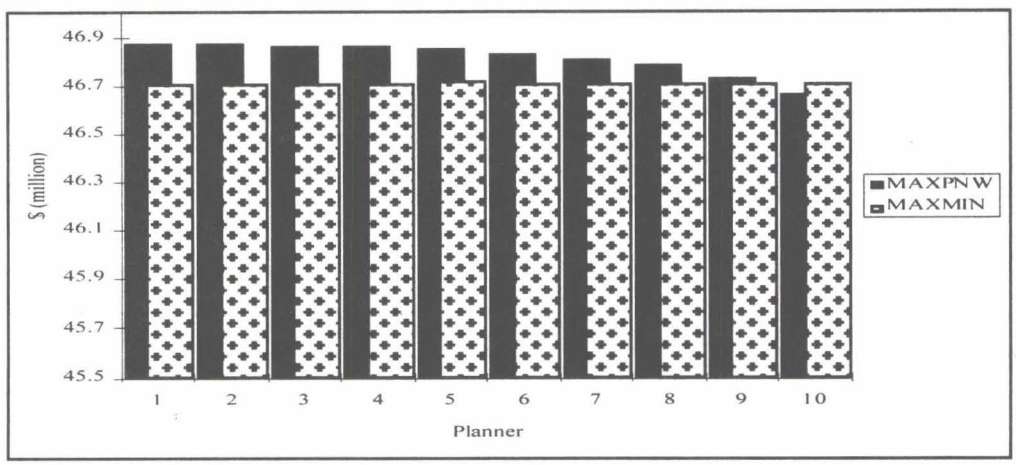

Figure 2.—*Comparison of PNW by Planner—OLD initial condition.*

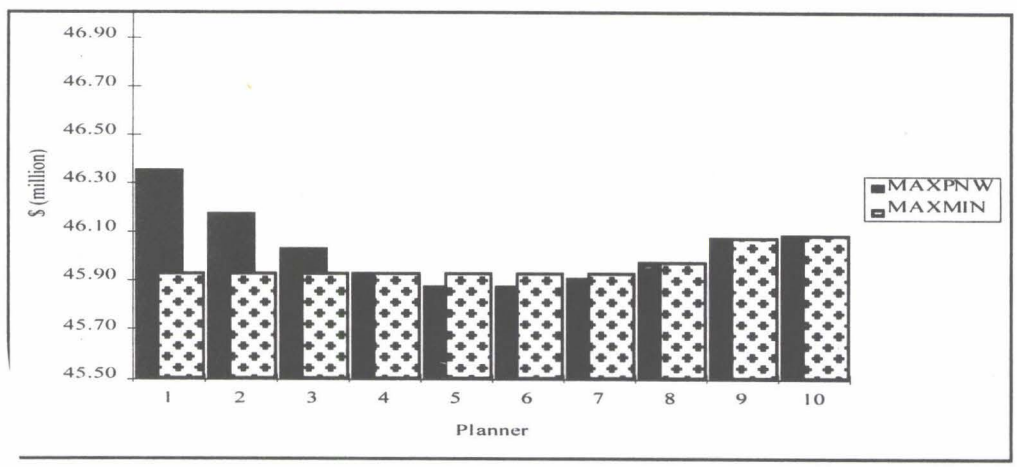

Figure 3.—*Comparison of PNW by Planner—YOUNG initial condition.*

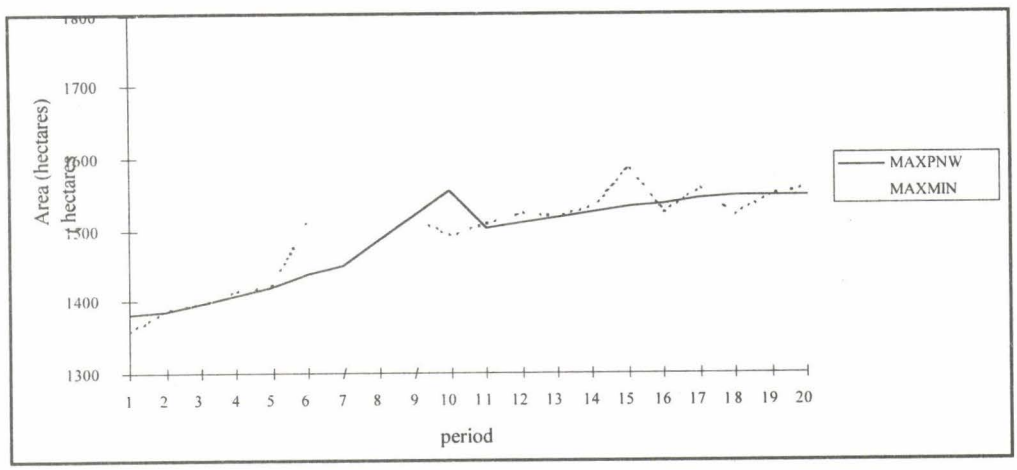

Figure 4.—*Comparison of Harvested Area per Period—EVEN initial condition.*

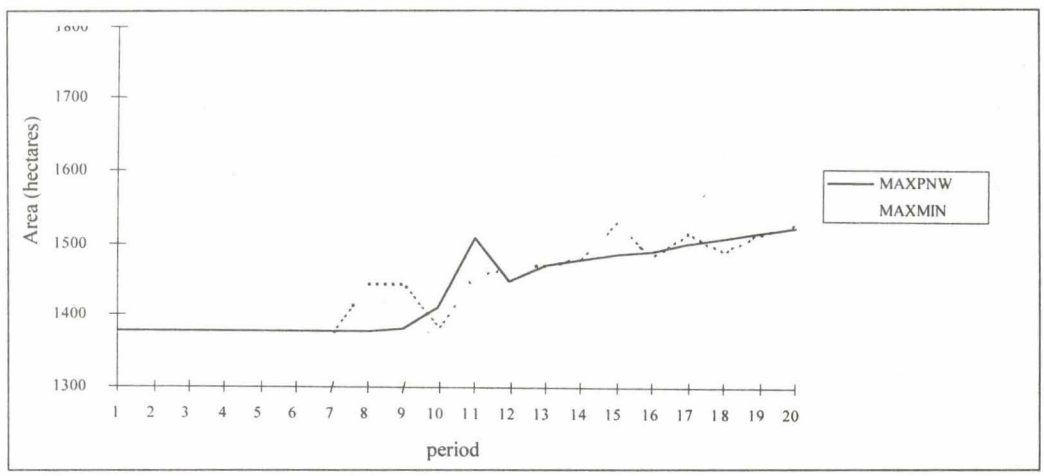

Figure 5.—*Comparison of Harvested Area per Period—OLD initial condition.*

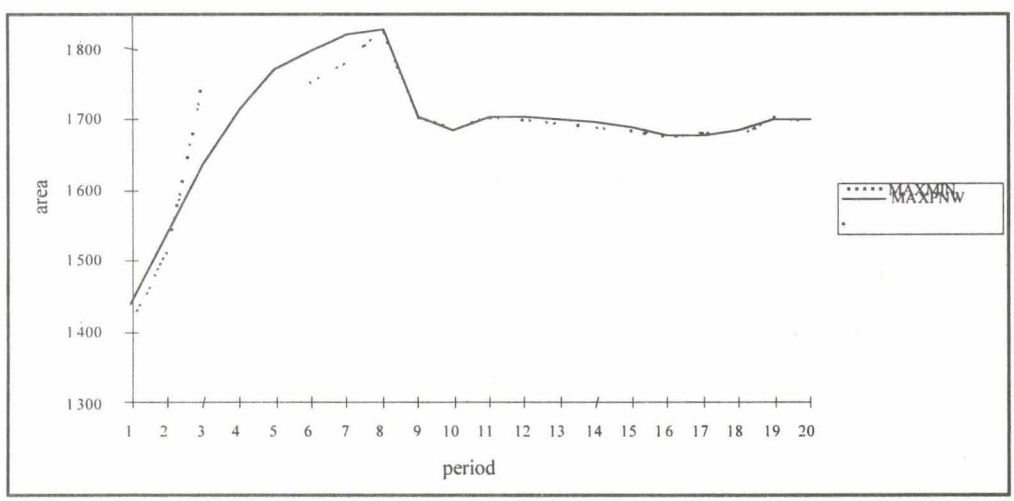

Figure 6.— *Comparison of Harvested Area per Period—YOUNG initial condition.*

DISCUSSION

The PNW results exhibit a pattern consistent with a Rawlsian equity approach. The MAXMIN approach required early period planners to accept a lower PNW to benefit later period planners. For two of the initial conditions (EVEN and OLD), the MAXMIN approach required the majority of planners to lower their PNW for the benefit of one or two planners. The amount of PNW given up exceeds that gained by the late period planners. The results suggest that in these cases early planners have limited ability to transfer PNW to future planners by changing activity patterns. In a Rawlsian bargaining situation where all planners select the alternative, it is not clear that future planners would prefer the MAXMIN approach over the MAXPNW approach for the EVEN and OLD conditions. The results for the YOUNG initial condition more clearly represent a reasonable Rawlsian solution. In this case, only the first three planners are required to lower their PNW in order to benefit the next four planners. The remaining three planners would be indifferent to the approaches.

The pattern in hectares harvested by period explains the PNW results. There is a set of periods in which the area harvested under MAXMIN is greater than under MAXPNW, followed immediately by a set of periods where area harvested is lower under MAXMIN. The volume removed for these periods is constant, so that the net revenue in any period is lower the larger the area harvested, since revenue depends on volume and costs depend on area harvested. The same periods where the MAXPNW harvested area is higher than the MAXMIN harvested area, is where the PNW for the planners under MAXPNW is lower. The MAXPNW formulation raises PNW for early planners by scheduling the most valuable forest for harvest in the early periods, and delaying the harvest of less valuable forest to later periods. In order for the MAXMIN formulation to increase the PNW for the later planners, less value can be removed in the early periods, particularly period one. The MAXMIN formulation schedules the harvest of younger, less valuable forest in earlier time periods, in order to raise the PNW for later planners. The result is that no one future planner is sacrificed in order to raise an earlier planner's PNW.

CONCLUSIONS

IE is about the passing on of options to the next generation, so that they have sufficient resources and flexibility to solve their own problems and cater to their own needs. We did not attempt to meet this ideal in this paper. Rather, we started with a standard formulation of an LP-based forest planning problem and varied the perspective from which it was solved to modify the distribution of PNW. The intent was to consider ways of modifying a standard formulation to more explicitly address the time dimension. Such a modification was accomplished by simply including accounting rows that model the perspective of future planners. This formulation allowed consideration of a form of Rawlsian equity, which focuses on making the worst planner better off. For two of the three initial conditions examined in this paper, the IE trade off involved raising the PNW outcomes for a small number of planners at the expense of all other planners. From an equity viewpoint, one could argue either way as to whether this trade off is good or bad. The important point is that the model formulation allows this type of trade off to be explicitly examined in the first place.

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HOW CAN WE ESTIMATE THE COST OF NATURE CONSERVATION?—SWEDISH CONDITIONS

Lars Rytter and Martin Werner[1]

ABSTRACT. —In Sweden, domestic resources of wood from deciduous species are limited. Because of high demands for the hardwoods both from forest industries and nature conservation, a solution that satisfies both parts is needed. This paper gives an example of how we approach the problem of evaluating the cost of nature conservation at the stand level. There are three main parts identified in the estimate: (1) the values of the selected trees themselves, (2) the cost of withdrawing their influence areas from future forest production, and (3) the costs for special management in order to keep the selected trees in desirable condition.

INTRODUCTION

Hardwoods constitute 15.5 percent of the total growing tree stock in Sweden, which in 1990 amounted to 2.7 billion cubic meters (m^3) (Berg *et al.* 1996). The main hardwood species is birch, both silver birch (*Betula pendula* Roth.) and downy birch (*B. pubescens* Ehrh.), constituting two-thirds of the hardwood volume. Other important deciduous species for forestry in Sweden are, in order of decreasing volume, aspen (*Populus tremula* L.), alder (*Alnus glutinosa* (L.) Gaertn. and *A. incana* (L.) Moench.), oak (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.), beech (*Fagus sylvatica* L.), and ash (*Fraxinus excelsior* L.) (National Board of Forestry 1996b). The consumption of broad-leaved pulpwood and timber exceeds the domestic harvest by 2 to 3 million m^3 annually. The deficit is mainly imported as birch from the Baltic States and Russia. In addition, as a member of the European Union, Sweden is involved in a situation where the demand for wood produced within the community will increase because of a policy aiming at decreasing the importation of tropical hardwoods.

In recent times, the awareness of and demands for biological diversity have increased significantly. Consequently, the pressure on the hardwoods has become higher. The Swedish Forestry Act of 1994 (National Board of Forestry 1994) stresses that hardwoods should be kept in conifer stands if the site is suitable and that nature and culture conservation demands shall be respected to a certain limit by the forest owner. Other organizations have complemented the guidelines of the act, although to different levels. The forest companies are also planning and using silvicultural methods that consider nature conservation. Because of the limited resources of wood from deciduous species in Sweden and high demands both from forest industries and nature conservation, a solution that satisfies both parts is of utmost importance. Some of the activities within the newly started south Swedish project "Improved utilization of hardwood for industrial processing" work in this field.

The aim of this paper is to compile and structure the varying demands placed on nature conservation from different sources and to describe and evaluate the costs involved when taking the demands into consideration. Realistic case studies will examine the costs of nature conservation.

RECOMMENDATIONS FOR NATURE CONSERVATION

Due to a widespread human population and a culture where wood has been a main prerequisite for survival, virgin forests in Sweden are rare and mainly located near the timberline in the mountains. Sweden had already introduced forestry in the beginning of this century to counteract the threat that human culture has presented to the forests. It has forced the forest owner to perform reforestation. Since then, the standing tree volume and annual increment has increased considerably. Thus, Sweden has had sustainable forestry in terms of wood production for almost a century. However, in the view of the Rio Declaration of 1992 (United Nations 1992, Schlaepfer 1997), sustainability includes more aspects of forestry than wood production. Therefore, a major

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change in the Forestry Act was adopted in 1994: environmental aspects, in terms of preserving biological diversity, were given the same importance as wood production. To fulfill the environmental aspects, two main types of actions are required: (1) particularly valuable biotopes (key habitats) had to be withdrawn from forestry; (2) general environmental considerations and measures had to be undertaken in connection with silvicultural treatments of all stands.

Although there is a general understanding of the need to preserve biotopes, there are discussions on how to cover the costs and the time available for completion. An estimated 5 to 10 percent of the productive forest area will be withdrawn from forestry as a result of this preservation. Many different ideas exist on how to undertake general environmental considerations and measures in connection with stand treatments. To solve this question, attempts have been made to work out an agreement to certify Swedish forestry according to the guidelines of the Forest Stewardship Council (FSC). So far this has failed, and a solution is not to be expected shortly. Therefore, the following ideas, presented by various organizations, will still be under debate.

The National Board of Forestry is the authority responsible for implementing the Forestry Act. Since the act does not prescribe details, the Board has worked out an activity plan comprising several recommendations on different scale levels (i.e., landscape and estate scales) (National Board of Forestry 1996a). The act stresses the need for more old, big trees and for an increasing amount of dead wood. This demand is especially valid for broad-leaved trees, as an increasing proportion of these should, in general, favor biodiversity. Examples are given on how to achieve the biodiversity goal on different types of estates. The Forestry Act gives the following recommendations for preserving trees on an estate in southern Sweden where broad-leaved trees dominate the landscape:

- In conifer stands, five trees per hectare (ha) should be left as "eternity trees." Birch, aspen, willow, and wide-crowned spruces are considered the best choices.

- In stands with broad-leaved species, 10 trees per ha in terms of wide-crowned oaks, aspen, and birch are given priority and should remain.

- Finally, in mixed stands with an extremely large number of different tree species, 15 big trees per ha are recommended to be left.

So, depending on the prerequisites, a varying number of trees per ha should not be harvested to promote biodiversity.

The Swedish Society for the Conservation of Nature, in a joint document together with World Wildlife Fund (1995), has presented a demand for leaving at least 10 percent of the standing volume measured as basal area as a link between the old and the new stand. Therefore, at least 10 trees per ha should be left on the clearcut where possible. In combination with this, 20 old "eternity trees" per ha should, as an average, be left in connection with clearcuts. Their function is to turn into dead wood in the future. In order to immediately increase the amount of dead wood, three "tall stumps" per ha should also be produced when clearcutting.

The worldwide demand for sustainable forestry has been a challenge to Swedish forest companies like AssiDomän, Korsnäs, MoDo, SCA, and Stora. Environmental policies have been published to meet the demands. For the forestry part, these policies generally have a structure comprising ecological landscape planning, nature-like silvicultural methods, better site adaptation in terms of the right species in relation to site, and ecological or environmental final accounts. The idea is to show the improvements for a number of ecological goals by the annual accounts. The companies are generally prepared to set aside endangered biotopes to a noticeable extent. Although a number of ecological goals and considerations are clearly described, the general precautions taken in connection with silvicultural treatments are normally not specified. However, the policies mention leaving trees, preferably those in groups, in connection with harvest operations. At least one company, Korsnäs, is already certified according to ISO 14001 for the forestry part.

Private forest owners, many of whom are organized within Forest Owners' Associations, own one-half of the productive forests. Their forests are generally more diverse in terms of management intensity and many other aspects compared with the company forests. The average estate consists of only 50 ha, which constitutes a specific problem in the case of forestry certification. Voluntary nature conservation agreements and ecological forest inventory plans are two instruments used to reach the combined production and environmental goals. A voluntary nature conservation agreement is a 1-year agreement (which can be prolonged one year at a time) between the forest owner and his association. In these agreements, the owner must leave at least 5 percent of the area for the single purpose of enriching biological diversity. They also must be more ambitious in terms of environmental precautions than demanded by the Forestry Act on the rest of their lands. However, these agreements are not sufficient for satisfactory protection, and these organizations state very clearly that it must be the community that takes overall responsibility for reserving sufficient areas to protect endangered biotopes. As the Forest Owners' Associations are managing small

estates, it is natural that they claim that ecological considerations must be seen from a landscape perspective, from which ecological inventory plans are made up on the estate level. The plans shall promote long-term sustainable forest management on the different estates within their own prerequisites. Recently, the Forest Owners' Associations declared that private forest owners cannot meet the economic responsibilities required for a FSC certification. It is interesting to note that one of the associations, Södra, recently stated that many forest owners, in the trend towards more nature-like silvicultural methods, have reduced reforestation measures and noncommercial thinnings to a degree where wood production might be endangered, presumably without any noticeable ecological advantages.

ECONOMIC ELEMENTS OF THE NATURE CONSERVATION COST

Among possible economic elements influenced by nature conservation, three were identified as important for the economy of forestry. First, the standing trees themselves constitute a significant value, which increases with age both in forestry and nature conservation. Second, the cost of withdrawing the influence areas of trees from forest production (i.e., the expected land value) has to be estimated. The influence areas can be separated in light competition areas and nutrient/water competition areas. In general, the final spacing indicates the influence areas of mature trees. Third, the costs for additional management directed towards protecting selected preserved trees have to be considered. In our case studies, we assumed that this third element was close to zero (i.e., income and costs were nearly equal). It is, of course, possible to find other elements that can affect forest economy, such as more expensive logging caused by the requirement to respect nature conservation. However, it was assumed that these other costs could only marginally influence the calculations, and they were consequently left without further attention.

CASE STUDIES

With the following two case studies of forest stands, we discuss the effects of rotation time and wood value on the cost for nature conservation. Oak forests, with long rotation periods (often more than 120 years) and high wood values at later stages, will be compared with birch, a forest type with faster rotation (about 50 years) but lower final wood values. With these case studies, we intend to demonstrate the effect of general consideration to nature conservation. Areas set aside as reserves or key habitats are not included in the discussion. In addition to the proposed number of preserved trees per ha, 10 and 20, we have also used 3 trees as a minimum number for nature conservation.

Stand of Old Oaks

This type of stand was included because oaks represent a hardwood species with high wood value, up to 2,700 SEK per m^3 (about $340) for veneer logs. Oaks are also common in the southern part of Sweden and old specimens have a significant biological diversity value (Weslien 1993, Ahlén *et al.* 1996).

The selected stand is about 120 years old and situated close to the Ekebo field station of the Forestry Research Institute of Sweden (latitude 55°57′N.; longitude 13°07′E.; alt. 80 m). The oaks are growing on a fresh and well-drained fertile soil (productivity 5 to 6 m^3 of stemwood per ha per year), but have only been extensively managed. Thus, the quality of the trees is not optimal. However, this is a common situation, so the selected stand can be considered as representative. The trees have reached their climax, and an extension of rotation time will not improve quality but instead lead to degeneration of crowns and adventitious branching. The spacing is somewhat too dense for the final stage of the stand and increases the risk of crown competition and dying branches. Below the oaks, a second tree layer of mainly young ash plants has naturally regenerated.

In two circular sample plots of 314 square meters (m^2) each, all trees were counted and measured for diameter (table 1). On these plots, a total of five old, big oaks were found. These trees were measured for height, diameter, crown projection area, crown length, and value (table 2). Table 1 shows a dense new plant generation with a high value of basal area where ash and hazel dominate. The spacing of the old oaks is about 70/ha with a mean tree basal area of 33 square decimeters. The stand basal area of the top layer trees can be estimated to 23 m^2/ha. In an optimal situation there should be fewer but thicker trees and a basal area of about 20 m^2/ha. The importance of thick stems for high wood values can be seen from table 2. Not only was the stand denser than recommended, the trees were also grouped and the crowns competed with each other. On the sample plots, the total crown projection area was 85 percent of the sum of the individuals, i.e., 30 percent of the crown projection area had competition from a neighboring tree. The wood values of the oaks (table 2) were only about half of what can be expected for corresponding diameters in well-managed stands, except for tree 2:146, which contained a veneer log and thus reached 85 percent of expected value. A mean wood value of 2,281 SEK and 70 oaks per ha gives a total wood value of 160,000 SEK per ha.

Table 1.—*Stem number (n), diameter of stem of mean basal area (Dg), and basal area (G) for the different tree species found on the sample plots. All trees with a height of 1.3 meters (m) or more are included.*

Tree species	n	Dg	
	no ha^{-1}	*cm*	*m^2 ha^{-1}*
Ash (*Fraxinus excelsior*)	5,396	1.8	1.48
Beech (*Fagus sylvatica*)	48	2.0	0.02
Bird cherry (*Prunus padus*)	143	2.8	0.09
Crab apple (*Malus sylvestris*)	127	6.4	0.56
Hawthorn (*Crataegus* sp.)	128	1.7	0.02
Hazel (*Corylus avellana*)	700	2.3	0.30
Norway maple (*Acer platanoides*)	32	2.7	0.02
Pedunculate oak (*Quercus robur*)	143	46.0	26.4
Rowan (*Sorbus aucuparia*)	96	3.5	0.09
Sallow (*Salix caprea*)	32	2.8	0.02
Silver birch (*Betula pendula*)	175	3.8	0.12
Wild cherry (*Prunus avium*)	112	3.8	0.32
Totals and mean	7,132	7.2	29.4

Table 2.—*Data on the five dominating oaks on the sample plots. The following characters were recorded and estimated: diameter in breast-height on bark (d.b.h.), tree height above ground (H), live crown base (Hc), crown projection area (Cpa), tree volume under bark (V) calculated from volume functions of Hagberg and Matérn (1975) and bark functions of Söderberg (1986), and tree value on root as estimated by a professional log purchaser.*

Tree no	d.b.h.	H	Hc	Cpa	V	Value	
	cm	*- - - - m - - - -*		*(m^2)*	*(m^3)*	*SEK*	*US$*
1:38	58.3	25.0	3.8	43.5	2.97	1,051	133
1:117	73.2	25.5	2.3	151.3	5.13	2,822	357
1:220	51.3	21.5	5.0	76.0	1.98	703	90
2:89	70.0	26.2	3.0	100.1	4.71	2,686	340
2:146	69.7	24.5	6.9	114.2	4.46	4,143	524
Mean	64.5	24.5	4.2	97.0	3.85	2,281	289
Standard deviation	9.3	1.8	1.8	40.5	1.32	1,408	178

The expected land value has been calculated with information from Carbonnier (1975), Møller Madsen (1994), and Persson (1996).[2] By using the current price list (1996/1997) of the Forest Owners' Association Södra in southern Sweden, we obtained the figures of table 3 on net outcome and expected land value at different rates of interest. The economic consequences of leaving 3, 10, or 20 oaks per ha in the actual stand at 2 percent rate of interest have been compiled in table 4.

The general consideration to nature conservation that can be called for from the forest owner may not severely prevent forestry. The demands must be reasonable. These guidelines suggest that 20 or 10 oaks per ha, or 10 percent of basal area, reserved for conservation purposes is not realistic for rational economic forestry. Three trees is a more realistic figure to negotiate. If we consider a well-managed stand with 50 stems per ha remaining at the time of final cutting, the demand of 10 and 20 trees is even more unrealistic. These trees can be expected to have a final value of about 7,000 SEK each, which means that 40 percent or 140,000 SEK will be directly withdrawn with 20 trees from the landowner. Grouping the reserved trees had small effects in this case but will undeniably facilitate future logging.

[2] *Torvald Persson. 1996. Empirical data. Work performed within the commissioned south Swedish project "Improved utilization of hardwood for industrial processing." Södra. Personal communication.*

Table 3.—*Expected land value of future oak forestry at Ekebo with different rates of interest. For establishment and precommercial thinning of oak, a subsidy with 80 percent of the costs can be obtained, and this is included below.*

Year	Measure	Net outcome	Rate of interest		
			2 percent	3 percent	4 percent
			SEK / US$		
0	sowing + fencing	-4,000/-506	-4,000/-506	-4,000/-506	-4,000/-506
10	precommercial thinning	-500/-63	-410/-52	-372/-47	-338/-43
15	precommercial thinning	-500/-63	-372/-47	-321/-41	-278/-35
20	thinning	-1,954/-247	-1,315/-166	-1,082/-137	-892/-113
25	thinning + pruning	-4,056/-513	-2,472/-313	-1,938/-245	-1,521/-193
30	thinning	-408/-52	-225/-28	-168/-21	-126/-16
35	thinning + pruning etc	-5,792/-733	-2,896/-367	-2,058/-261	-1,468/-186
40	thinning	-476/-60	-216/-27	-146/-18	-99/-13
45	thinning	385/49	158/20	102/13	66/8
55	thinning	2,970/376	999/126	584/74	343/43
65	thinning	5,455/691	1,506/191	799/101	426/54
75	thinning	8,794/1,113	1,991/252	958/121	464/59
85	thinning	12,003/1,519	2,230/282	973/123	428/54
100	thinning	25,959/3,286	3,583/454	1,351/171	514/65
130	final cutting	267,703/3,3886	20,400/2,582	5,739/726	1,634/207
Total		305,583/38,683	18,961/2,401	421/53	-4,847/-615

Table 4.—*The cost of nature conservation, expressed as leaving 3, 10 or 20 trees per ha at final felling, in the oak forest at Ekebo. The economic elements consist of value of trees removed from forestry (Tree value) and expected land value at 2 percent rate of interest (Land value).*

Economic element	3 trees		10 trees		20 trees	
	SEK	*US$*	*SEK*	*US$*	*SEK*	*US$*
			Evenly distributed trees			
Tree value	6,843	866	22,810	2,887	45,620	5,775
Land value	813	103	2,709	686	343	5,417
Total percent of future net outcome	7,656	969	25,519	3,230	51,037	6,461
	2.5	2.5	8.4	8.4	16.7	16.7
			Grouped trees			
Tree value	6,843	866	22,810	2,887	45,620	5,775
Land value	691	87	2,302	291	4,605	583
Total percent of future net outcome	7,534	953	25,112	3,178	50,225	6,358
	2.5	2.5	8.2	8.2	16.4	16.4

Stand of Mature Birches

A birch stand was included because the two Swedish birch species alone constitute two-thirds of the hardwood volume in the country (Berg *et al.* 1996). The selected stand originates from crossings of plus trees of both silver birch and pubescent birch. The existing stand consists mainly of silver birch since it has superior growth. The original spacing was 7,000 plants per ha, which has been reduced to just below 200 trees today by several cleanings and thinnings (the stand is now 48 years old). The stand is located on a gentle east slope of the small hill Konga Klint at an altitude of about 135 meters (m) (latitude 55°58´N.; longitude 13°11´E.). Because of the plant material and proper management, the quality of the birches is significantly higher than generally found in the region. The current spacing is also sparser than normally recommended. The site index corresponds to a mean annual increment of wood of about 7 m^3/ha/yr.

A circular sample plot of 707 m^2 was placed in a representative part of the stand. Table 5 presents data describing this area. Wood values of the trees were calculated from empirical data on well-managed birch stands prepared by Torvald Persson, Södra (1996). Thus the calculated value and real value may differ somewhat.

Because the stand has not been optimally thinned, the rotation time for the stand will be extended about 12 years to 60 years, with no further thinnings. In order to estimate the dimensions and values of the birches at 60 years of age the following assumptions were made: (1) the height growth during 12 years on the actual site index was estimated to 2.2 m from Swedish yield tables (Fries 1964), (2) the diameter growth of the stem of mean basal area was found to be about 4 centimeters (cm) in 12 years in the age 50–60 years for the actual site index (Fries 1964, Oikarinen 1983), (3) individual wood values were taken from empirical curves for well-managed birches in southern Sweden prepared by Torvald Persson (1996).

With the above-mentioned assumptions, the wood value of the birches on the sample plot will increase from 2,600 SEK today to 4,000 SEK after 12 years, which corresponds to 57,000 SEK per ha. Because of high tree vitality and sparse spacing, with only 44 percent crown projection per unit of ground area, the growth calculations are probably underestimates. The fast increase in wood value can be explained by the fact that the butt log of most trees will grow into the valuable veneer log assortment where the minimum diameter is 30 cm on bark. The expected land value (table 6) was calculated by using information from Fries (1964) and Torvald Persson (1996).

The economic consequences of keeping 3, 10, or 20 birches per ha on the site at 2 percent rate of interest can be seen from table 7. Because of small overlapping of projected crown areas at the final harvest, no alternative of grouping trees was included.

In comparison with the oak stand, the values themselves are lower, and, because of a considerably larger number of stems, each stem is less critical if withdrawn from forestry. Nevertheless, the demands of 10 or 20 trees per ha means a severe drawback for the total economy of birch forestry aiming at high quality. It seems reasonable to discuss a preservation of three birches per ha.

DISCUSSION AND CONCLUSIONS

In terms of ecological effects of biodiversity-promoting treatments, lack of knowledge is the main drawback in the sustainable forestry option. The only measure so far to describe biodiversity-promoting treatments is the reduction of wood produced. No one is, for example, able to forecast the increase of endangered insect populations if 10 or 15 trees are left per ha. It is likely that many specific actions taken to enrich biodiversity will give no result at all, due to the very complex relations that exist in nature. However, it is generally a movement in the right direction. Detailed recommendations must be revised continuously.

It is obvious from the case studies that the number of trees that can be left by the landowner without severe economic loss has to be adjusted to the final spacing and values of different tree species. As was clearly seen, a definite number of preserved trees has a more serious impact in the oak than in the birch stand. Aspen and alder stands resemble the birch situation, while beech and ash stands come somewhere between oak and birch regarding tree value and final spacing. We also observed that leaving groups of trees had little effect on the loss of expected land value but may positively influence the stability of biodiversity and facilitate future logging operations. In an economic and well-managed forest, all trees left at final cutting have high values with small variations. Therefore, it will always involve important financial losses when preserving trees. Thus, one may argue that trees should be left in poorer stands with greater variability. In such stands, the wood value of trees of low quality may be nearly negligible.

Table 5.—*Stand data on the birches at Konga Klint recorded in March 1997*

Stand character	On the plot (707 m^2)	Per hectare
Number of stems	13	184
Diameter of stem of mean basal area (cm)	30.7	30.7
Dominant height (m)	26.0	26.0
Basal area (m^2)	0.96	13.6
Volume on bark (m^3)	11.0	156
Crown projection area (m^2)	311	4,400
Mean wood value per tree (SEK/$)	200/25	200/25
Total wood value (SEK/$)	2,600/329	37,000/4,684

Table 6.—*Expected land value of birch forestry at Konga Klint with different rates of interest. The thinning grades were 30-35 percent of standing tree volume and total wood production 400 m³ during 50 years. The felling costs were estimated to 250, 170, 150, 110, and 100 SEK per m³ at 15, 20, 25, 35, and 50 years of age, respectively. Final stem number is estimated to 200 per ha.*

Year	Measure	Net outcome	Rate of interest		
			2 percent	3 percent	4 percent
			- - - - - - - - - - - - - SEK / US$ - - - - - - - - - - - - -		
0	natural regeneration	0/0	0/0	0/0	0/0
7	precommercial thinning	-3,000/-380	-2,612/-331	-2,439/-309	-2,280/-289
10	precommercial thinning	-1,000/-127	-820/-104	-744/-94	-676/-86
15	thinning	240/30	178/23	154/19	133/17
20	thinning	3,780/478	2,544/322	2,093/265	1,725/218
25	thinning	4,070/515	2,481/314	1,944/246	1,527/193
35	thinning	7,950/1006	3975/503	2825/358	2015/255
50	final cutting	7,5593/9569	28085/3555	17243/2183	10637/1346
Total		87,633/11,091	33,831/4,282	21,076/2,668	13,081/1,654

Table 7.—*The cost for forestry of leaving 3, 10, or 20 trees per ha at final felling in the birch stand at Konga Klint. The chosen rate of interest is 2 percent.*

Economic element	3 trees		10 trees		20 trees	
	SEK	US$	SEK	US$	SEK	US$
Tree value	930	118	3,098	392	6,196	784
Land value	507	64	1,692	214	3,383	428
Total	1,437	182	4,790	606	9,579	1,212
percent of net outcome	1.6	1.6	5.3	5.3	10.6	10.6

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SPECTRUM: AN ANALYTICAL TOOL FOR BUILDING NATURAL RESOURCE MANAGEMENT MODELS

Kendrick Greer and Bruce Meneghin[1]

ABSTRACT.—This paper describes the functional capabilities of Spectrum: a software tool for constructing linear programming-based forest management models. Spectrum contains a robust set of features that allow easy construction of the three components of a forest management model: current and future states of the forest and the natural processes that affect change, ecosystem management goals and objectives, and a range management actions that offer alternatives for achieving these goals. Flexible land stratification schemes allow the model to focus at the appropriate scale. Generalized Model 2 formulations enable representation of successional pathways and forest structure changes due to mortality and fire. Management goals, constructed as constraints in the model, can control any aspect of the model such as structural stage proportions, rates of harvest, critical habitat requirements, or budgetary limitations. Objectives can be created to minimize deviations from historical structural patterns, maximize joint species viability or minimize deviations from a variety of stakeholders' goals. Management actions that cover a wide range of treatment and timing options are easily constructed. Spectrum has been used to construct planning models for several national forests and has been used in several research studies. Attendance at recent training sessions has shown keen interest from U.S. forest industries as well as forest managers in foreign countries.

OVERVIEW

Spectrum (USDA Forest Service 1995) is a computer-based analytical tool designed to assist land managers with strategic planning. It was developed jointly by staff at the Ecosystem Management Analysis Center and researchers at the Rocky Mountain Forest and Range Experiment Station. With Spectrum, managers are able to model alternative resource management scenarios through time and use mathematical programming techniques to schedule activities which best meet their objectives. Although designed primarily for broad-scaled strategic planning, Spectrum is finding acceptance in smaller-scale tactical analyses pertaining to individual watersheds or similar project areas.

Spectrum is not a model per se, but a flexible tool that facilitates the model building process. It is analogous to an artist's blank canvas, brushes, and paints. Spectrum provides the building blocks to create a model, but like an artist's canvas it starts out blank. It has no inherent data or relationships, thereby providing the model builders with maximum latitude and flexibility. Many model builders can be involved in the construction of a single model. Ideally, an interdisciplinary team addressing integrated planning issues will use Spectrum to jointly build a model of the multiple-use interactions that exist or might exist in a forest environment. Once built, all members of the team can run the model and conduct sensitivity analyses relevant to their areas of interest.

Spectrum is similar to another analysis tool called FORPLAN (Johnson *et al.* 1986). FORPLAN served as the primary analysis tool for Forest Service land management planning since 1980 and its capabilities and limitations are well documented (Bailey 1986, Hoekstra *et al.* 1987). The Land Management Planning Critique (Hoekstra *et al.* 1990) in particular, found that despite being basically sound and providing good analysis, FORPLAN:

- is not user friendly;
- is difficult for analysts, managers, and the public to understand models and explain results;
- is expensive to run in terms of computer resources;

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- is time consuming to learn the system, build models, and do analysis;
- does not adequately account for spatial relationships within the management problems being modeled;
- does not address uncertainty and risk surrounding resource information; and
- relies on linear optimization techniques that are an inadequate representation of real world natural systems and management objectives.

Criticisms of FORPLAN, the agency's adoption of an ecosystem-based management policy, and changing technology led to the decision to develop Spectrum. Earlier emphasis on economic efficiency has shifted toward ecosystem sustainability and changed the focal point of analysis. The historical range of variability within an ecosystem has replaced production capability as a benchmark for analysis. There is a need to embed natural disturbance and other ecological processes within our models and to evaluate management in the context of longer temporal scales and multiple spatial scales. What is left behind on the landscape through time (its desired condition) has become more important, instead of just what has been harvested or taken.

Models built with Spectrum are envisioned to fulfill many needs of the planning process and informed decisionmaking. They can be used to formulate and evaluate alternative desired conditions for the various landscapes of the forest. A model can explore alternative pathways for achieving a specific desired condition. The resource interactions and effects of applying a variety of management actions to landscapes through time can be examined. Models can assist in developing feasible and sustainable management plans by scheduling activities subject to specific management objectives and constraints. The tradeoffs among alternative management plans can be explored in terms of ecological, environmental, and economic factors. Perhaps the greatest use of Spectrum models is for asking "what if" questions and doing sensitivity analysis on major assumptions and uncertain data. For example:

- what if we emphasize amenities over commodities?
- what if we allocate all suitable wildlife habitat to reserves?
- what if we have reduced budgets?
- what are the implications of our resource inventories being off 10 percent?
- how will our ability to provide the projected levels of goods and service be affected if insects impact 10 percent of specific landscapes?

SYSTEM COMPONENTS

Figure 1 portrays the components of Spectrum and their relationship to one another. Spectrum is accessed through a graphical user interface which presents sophisticated analytical capability for complex problem analysis in a user-friendly manner through "Windows-like" features such as point and click menus and pick lists. Within the interface the user will find:

- a data entry system with on-line help screens for model building and editing,
- a model manager to track multiple models,
- a run manager for executing models via the background analytical engine,
- a solution manager for creating customized solution reports,

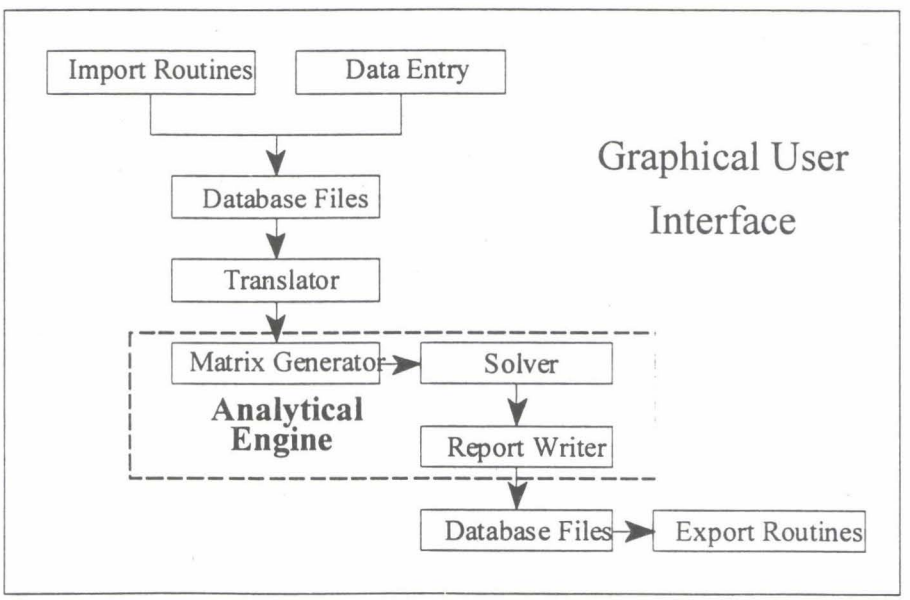

Figure 1.—*Spectrum system components.*

- graphical display of certain model data and solution information,
- utilities for data import and solution export.

Spectrum uses relational database structures to store all model data and solution results. These structures are xBase-compliant enabling a user to access them outside of Spectrum via popular database management systems such as dBase, FoxPro, or Access.

At the heart of Spectrum is the analytical engine, which generates a matrix for the linear programming algorithm, solves the matrix, and interprets the solution results into a series of reports and database files. Spectrum uses a commercial linear programming software package known as C-WHIZ (Ketron Management Science 1994) to solve the matrix. The analytical engine provides for very flexible and robust problem specification.

Spatial Specification

The primary data units in Spectrum are areas of land or analysis units. Analysis units can be contiguous with similar characteristics, discontiguous with similar characteristics, or contiguous with dissimilar characteristics, depending upon the needs of the analysis. The user has up to six attributes to describe the characteristics of each area of land. The number of allowable analysis units for a given model is virtually unlimited.

Contiguous analysis units (or contiguous parts of analysis units) can be grouped together into zones. Zones are used to address a higher level of scale than analysis units; typically they represent logical management units. The management of the representative analysis units within a zone can be coordinated. For example, all the acres within a zone must be managed as a wildlife reserve. Zones can also be used to model activities and outputs that occur on an area basis instead of an acre basis (which is the case for analysis units). For example, it usually makes sense to associate the amount of road building with the management choice of an entire area. Furthermore the user can control the timing of these activities so that, for example, only 25 percent of the road building occurs during the first time period.

Temporal Specification

Each Spectrum model has a specified time frame called a planning horizon. The planning horizon is broken into equal length intervals called periods. The user specifies the number of periods (up to 90) and the period length depending upon the needs of the analysis. Exploring sustainability issues would dictate a model with a long time horizon, while a model with small periods may be used for a budget analysis.

Management Actions

Management actions are characterized by two attributes, typically management emphasis and management intensity. They consist of a set of activities that when applied to specific areas of land results in a set of outputs and/or conditions. These sets of activities and outputs are packaged together in what is called a yield composite. The resource coefficients associated with each member of a yield composite are either listed in tables or described as a relationship to another member. For example, the amount of logging costs may be directly related to the amount of timber volume removed.

The relationship may be discriminated by the type of management (emphasis and intensity), the type of land it is being applied to (via its attributes), and the type of vegetative treatment that is occurring. The habitat for a particular species of wildlife may be different following a shelterwood treatment than a clearcut.

Economic information can be applied to any of the activities or outputs as appropriate. The coefficients can be discriminated by the type of management, the land area, the type of vegetative treatment, and descriptors of the resource yields. For example, timber from 18" diameter logs may be more valuable than timber from 12" diameter logs. Economic information can also be trended through time and derived from price/quantity demand data.

Each management action has a schedule of timing options associated with it. The schedules can be either time-based or age-based. Time-based schedules specify when, during the planning horizon, the management action can first begin. Age-based schedules utilize the vegetation age for the same purpose. Spectrum facilitates defining schedules for uneven-aged, shelterwood, and clearcut management regimes.

Multiple Outcome Model 2 Formulations

In Model 1 formulations, each decision variable in the linear programming matrix represents possible management for a land area over the entire planning horizon. In traditional Model 2 formulations, each decision variable represents possible management for a land area over the life of the stand with a set of decision variables representing the generations of stands that can occur over the planning horizon (Johnson and Scheurman 1977). However, each decision variable recognizes only one outcome at each age from regeneration of the stand to regeneration harvest. Spectrum improves upon traditional Model 2 in a number of ways. First, acres can split among multiple regeneration classes. This, for example, allows for the explicit recognition of regeneration failure.

Second, acres can pass to regeneration classes any time during the rotation, allowing explicit recognition of mortality. Third, acres can move to other classes besides regeneration classes—that is, classes with stand ages other then zero. This allows embedding probabilistic outcomes into the model. For example, models can be built to represent multiple outcomes following commercial thinning or multiple outcomes of catastrophic events.

State and Flow Variables

To address ecosystem management issues, it is important to be able to embed simulation of ecological process and natural disturbance modeling within our planning models. Multiple outcome Model 2 formulations provide us with some of this capability as does the use of state and flow variables. An example of a state variable is the number of animals of a particular species in a given watershed. An example of a flow variable is the number of animals moving into or out of that watershed. These variables are used in linear and non-linear equations (using linear approximation techniques) which can cross over all or just a subset of all management actions. The equations can have a temporal dimension as well as an initial condition. Once defined, the variables can be subsequently used in constraints and objective functions. State and flow variables make it possible to derive model solutions using non-linear ecological relationships as the basis for selecting among a range of possible management actions.

Constraints

Specifying constraints in Spectrum is as easy as writing a linear equation. The variables in the equation are called constraint variables, which are simply an activity or output for a subset of your model (specific land areas, management actions, vegetative treatments, stand ages). Constraints have a temporal dimension to them but it does not have to be the same for both variables. A few examples of constraints are:

- acres of elk habitat in period 7 must be at least 7,000 acres.
- acres of early successional stage in periods 1 and 2 must be at least 42 percent of the acres of late successional stage in periods 2 and 3.
- timber volume cannot decrease by more than 10 percent in each successive time period.
- amount of recreation in area A in periods 1 and 2 must exceed the amount of recreation in area B in periods 2 through 5 by at least 100 units.

Mathematical Programming Options

Spectrum offers an array of optimization techniques and flexible specification of objective functions. In addition to traditional linear programming, cardinally weighted goal programming and mixed integer programming solution techniques are available. Linear programming optimizes a single objective either through maximization, minimization, MAX/MIN, or MIN/MAX. The MAX/MIN formulation maximizes the minimum level of a critical resource throughout the planning horizon, while MIN/MAX minimizes the maximum level of an undesirable outcome.

Goal programming tries to achieve several objectives simultaneously. A goal or target is specified for each objective and a solution is sought that minimizes the weighted sum of deviations from these targets. Individual objectives may have different degrees of importance reflected in the penalty weight attached to deviation from their targets. In addition, an individual objective may have different penalty weights depending upon the direction and magnitude from the target, as well as the time period. The user has the option of minimizing under-achievement of goals, over-achievement of goals, or both.

SPECTRUM APPLICATIONS

Spectrum has seen growing use since its initial release in February, 1996. Several models have been constructed for national forests in the Pacific Northwest and the Rocky Mountains. Spectrum has also been adopted for use by private forest industry in the U.S. and by public forest managers in Australia. Typical of models being developed are goal programming formulations to try to create a mix of successional stages distributed spatially (generally by watersheds) throughout the forest and natural disturbance models showing the effects of change agents such as fire, insects, and disease based on historical and estimated probabilities.

Researchers at the Rocky Mountain Forest and Range Experiment Station have used Spectrum in a number of their studies. Hof *et al.* (1994) utilized a mixed integer formulation to optimize the spatial layout of management actions for providing wildlife habitat over time. Bevers *et al.* (1995) developed wildlife species viability optimization models to convert a given set of initial forest conditions, through a combination of natural growth and management treatments, to a forest system which addresses the joint habitat needs of many wildlife populations over time.

Attendance at Spectrum training sessions and requests for software and training have shown keen interest in Spectrum throughout the world. Training sessions have been given in Bolivia and at the European Forest Institute in Finland. A number of National Forest offices have retrieved the software and have begun to use it for analysis in support of Forest Plan revisions. Other government agencies, universities, timber corporations, consulting groups, and several land management agencies in foreign countries have also requested Spectrum software and have participated in user training.

TECHNICAL SPECIFICATIONS

Spectrum requires a 386 or better PC with 16 megabytes of memory and a mouse. Large models can require up to 200 megabytes of free hard disk space. If you use a 386 machine a math coprocessor is required. C-WHIZ from Ketron Management Science is needed for solving models, otherwise the rest of the software is available from the Ecosystem Management Analysis Center free of charge. The mixed integer programming option requires the MIP module of C-WHIZ, which must be purchased separately from Ketron. A version of Spectrum is available that requires only 8 megabytes of memory but only 20 time periods can be used for analysis.

Spectrum Release 1.5 is currently available. For information on how to obtain the software or user documentation, please contact Kathy Sleavin—[Phone: (970) 498-1833] [Fax: (970) 498-1660] [Email: ksleavin/rm@fs.fed.us].

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NEURAL NETWORK AND GIS DECISION SUPPORT SYSTEM: A MICROCOMPUTER APPLICATION TO PREDICT FOREST FERTILIZATION RESPONSE IN CENTRAL WASHINGTON

Roberto A. Avila and James A. Moore[1]

ABSTRACT.—This paper summarizes development of a neural network and Geographic Information System decision support system (NNGIS-DSS) microcomputer application designed to help forest managers predict tree response to forest fertilization operations in the Central Washington Region of the Inland Northwest. This system uses distinct software packages within an integrated personal computer development environment using Visual Basic as the front-end user interface. First, the user can consult any geographic region of interest for which tree growth response attributes exist. Values are then input from an ASCII file or from an Excel spreadsheet. Once the region is chosen, the mathematical computation is performed that converts the data into a matrix format through Excel LINK. The computations are accomplished to facilitate MATLAB and its Neural Network Toolbox execution. At this point, a combination of ecological and tree growth response input and output data for Douglas-fir tree species are simulated based on an already trained neural network architecture that predicts tree volume growth response, volume in cubic feet per acre, resulting from 200 or 400 pounds of nitrogen fertilizer applied per acre. Once the network is trained the user specifies the inputs from inventory, and the program computes appropriate output values. These same user inputs are also spatially queried through MapObjects. Next, a related operation within a MS Access data base table, an Excel worksheet, and a MapObjects table (associated with a stand map layer inside the region boundaries) is achieved. This results in geographic stand location and visualization, and serves for data analysis and interpretation. Finally, the system produces outputs that include maps, tables, graphs, and a summary report. The communication among the different software is intended to be transparent to the user as accomplished by Visual Basic and MATLAB programming code. Development of this microcomputer application is in its early stages.

INTRODUCTION

Decision support systems (DSS) can be very useful for making forest management decisions. DSS vary in scale, design, field of interest, model development, and evaluation. In the Inland Northwest, two well known existing decision support systems in forestry are FORPLAN and the Forest Vegetation Simulator (FVS). In national and private forest planning, FORPLAN has been a useful tool to help forest managers plan future operations. This software uses linear programming for system functional resource planning to reach an optimal solution based on decision variables and operational constraints (Johnson 1986, Iverson and Alston 1986, Kent 1989). FVS, the former PROGNOSIS model, is an individual tree-distance independent growth and yield model that uses forest inventory input data to project the development of forest stands over time. It allows stand comparisons of simulated silvicultural prescriptions and can be used to produce managed stand yield tables. Currently, Landscape Management System (LMS) is being developed by the University of Washington. It groups pieces of software to bring management, summarization, and visualization about forest stands at a landscape management level (Oliver 1996).

DSS technologies have been applied in agriculture and forestry with great success, but still these systems need to evolve to better serve users' expectations. Around the world, decision support systems dealing with agricultural fertilization operations have been developed in the form of expert system technologies. A computer application designed to advise farmers to predict the amounts of phosphorous, sulphur, and potassium fertilizers was

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developed by Lakhan and Ballantyne (1996) for use on the South Island of New Zealand. ENID is an expert system for fertilizer prescriptions that mixes explicit and implicit knowledge into a format helpful to forest managers involved in plantation nutrition in the Cape Province of South Africa (Payn *et al.* 1989). Stage *et al.* (1990) added a routine to the Prognosis Model for Stand Development that predicts tree growth response to fertilization applications of 200 lb. nitrogen.

The current project includes both quantitative and qualitative (forestry expert's knowledge) data as the basis for a computer application to assist in making forest fertilization management decisions in the Inland Northwest. The Intermountain Forest Tree Nutrition Cooperative (IFTNC) has begun to formally structure the fertilization operations decision-making process resulting from extensive data gathering and analysis through the past 15 years. The development of an expert system for forest fertilization based upon both a knowledge-based and quantitative data interpretation and analysis is the focus of this research. A spatial component is also incorporated to understand ecological input data processes and management. The entire approach is designed under the premise of input, process, and output system components. Initially the Central Washington region is used as prototype area for system data gathering, interpretation, and analysis. It also includes a Boise Cascade Corporation ecosystem management area utilized for system evaluation and testing. The project deals with the design and use of an integrated computer development environment that includes artificial intelligence, relational data bases, and Geographic Information Systems technologies to predict response to operational forest fertilization. The system predicts Douglas-fir growth response for a 6-year period and locates forest stands for fertilization operations based on treatments of 200 and 400 lb. of nitrogen per acre. The system is site specific, flexible to updates as new data are acquired, and provides for rapid computer prototype development.

Specific objectives are:

- Determine the type of computer deployment or development platform on which the system will be based;
- Accomplish automation of the product with the latest and state-of-the-art integrated development programming software including an easy to use Graphical User Interface (GUI);
- Employ a mathematical modeling approach methodology that will be used and implemented in the modeling component of the system;
- Design a system architecture that explains the system flow components and connectivity;
- Incorporate Relational Database Management System (RDBMS) for system operation, analysis, and reporting; and
- Create an application demonstration outlining the main components of the system prototype.

This research project is a work in progress at its initial stage and it will be expanded to produce a finished prototype. Following are some of the tasks accomplished to fulfill the above objectives.

METHODS

Study Area

The input/output data set from 17 IFTNC installations (a six-plot layout per installation) to model the system comes from the Central Washington region of the Inland Northwest. This region comprises both the Central Washington North and South sub-regions of the IFTNC. The evaluation and testing data set is the Teanaway ecosystem management area of Boise Cascade Corporation covering an area of 50,000 acres. A map of the study area is shown in figure 1.

Data Collection

Data collection includes quantitative and qualitative parameters pertaining to the above study area. The attribute values are from a designed fertilization control system (Avila 1997), entailing four main types of data: forest stand structure, forest stand diversity, individual tree measurements, and forest site quality characteristics. The input/output attribute list is given in table 1.

System Development

NNGIS-DSS is designed and operated in a Personal Computer (PC) environment and it can be used under Windows NT 4.0 workstation or Windows 95 operating systems. A Pentium 100 or higher machine for running time is required. Also, 32 Megabytes of random access memory (RAM) is the minimum requirement for efficient system performance. This application uses distinct software packages within an integrated computer development environment. The system design comprises three main module components: mathematical, data base, and visualization.

System Codification

Communication among the distinct software packages is intended to be transparent to the user accomplished by Visual Basic version 5.0 (VB5), a Microsoft desktop Integrated Development Environment (IDE) product. VB5 is used as the front-end user interface for the application project. The new features of VB5 that include wizards, value tips, statement completion, and new object browser (Fawcette 1997) will significantly

Figure 1.—*Map of the Central Washington North and South regions and the Teanaway ecosystem management area.*

improve the fertilization assessment tool programming capabilities throughout a harmonized design process including Data Access Objects (DAO), Object Linking and Embedding (OLE), and Dynamic Data Exchange (DDE) protocols. MATLAB version 4.2c.1 (MathWorks 1996) plus its Neural Network Toolbox version 2.0b (Demuth and Beale 1995) will bring the artificial intelligence features into the system for an effective, powerful, and cutting-age mathematical modeling approach. MapObjects (ESRI 1996) is a set of mapping software components that will be able to add the stand location and visualization component plus data connection, analysis, and management.

Neural Network and Geographic Information System Decision Support System (NNGIS-DSS)

Following is an explanation of the system design flow architecture. This section explains and illustrates the NNGIS-DSS fertilization prediction tool. Using the stand as the unit of measurement and quantification, NNGIS-DSS will help to predict and locate forest fertilization opportunities based on users input. The NNGIS-DSS communication design architecture is diagrammed in figure 2.

The system is fed by an integrated input data base (Avila 1997) which comprises data from any of the geographic regions of interest. Two types of data bases are included in the system: quantitative and qualitative. The quantitative data involve attribute values from each of the fertilization control system sub-components derived from both field data collection and some literature sources, as well as spatial attribute data from both Geographic Information Systems and Global Positional Systems data bases (see table 1). The qualitative data base encompasses knowledge-based data from experts involved in silviculture operations and research that reinforces system interpretation and analysis.

How does the system operate? To start training the network, MATLAB requires the data input/output formatted either as a plain ASCII file or as an Excel sheet. The Excel sheet format is recommended because it communicates with MATLAB as a dynamic data exchange (DDE) server, which is accomplished by an extension to Excel called Excel Link (MathWorks 1996). The first shade box (fig. 2), NNT training data set, is the Neural Network Toolbox engine that computes the input/output parameters for training the network. An explanation of the methodology for training the network parameters for Central Washington data is provided in Avila *et al.* (in prep.). The mathematical module already interpreted, analyzed, and tested for system functioning, predicts tree growth response based on 200 and 400 pounds of nitrogen per acre during a 6 year period. Once training has occurred, the system is ready to compute prediction results based on user inputs. The second shade box (fig. 2), includes the prediction component (desired outputs), plus the relational data bases to move between MS Access, and MapObjects used for system information

Table 1.—*Central Washington input/output attributes list, their units, and sources used to develop and parameterize the prediction*

Description	Units	Source
Inputs		
Longitude	Decimal degrees	GPS[1]
Latitude	Decimal degrees	GPS
Elevation	Feet	GPS
Aspect	Degrees	IFTNC data base
Slope	Percentage	IFTNC data base
Initial trees	Trees per acre	IFTNC data base
Initial basal area	Square feet per acre	IFTNC data base
Initial volume	Cubic feet per acre	IFTNC data base
Initial mean diameter	Inches	IFTNC data base
Crown competition factor	Numeric	IFTNC data base
Relative density index	Numeric	IFTNC data base
Site height	Feet	IFTNC data base
Species Composition		
Douglas-fir	Percentage	IFTNC data base
Grand Fir	Percentage	IFTNC data base
Ponderosa Pine	Percentage	IFTNC data base
Lodgepole Pine	Percentage	IFTNC data base
Western Larch	Percentage	IFTNC data base
Western red cedar	Percentage	IFTNC data base
Western Hemlock	Percentage	IFTNC data base
Vegetation Series		
Grand Fir	String	IFTNC data base
Douglas-fir	String	IFTNC data base
Western Hemlock	String	IFTNC data base
Rock Type		
Volcanic	String	GIS[2] data base
Sedimentary	String	GIS data base
Plutonic	String	GIS data base
Potassium level	K2O % content	GIS data base
Nitrogen rate	Pounds per acre	IFTNC data base
6-year Net tree vol. (Control)	Cubic feet per acre	IFTNC data base
Outputs		
6-year Net basal area response	Square feet per acre	IFTNC data base

[1] Global Positional Systems
[2] Geographic Information Systems

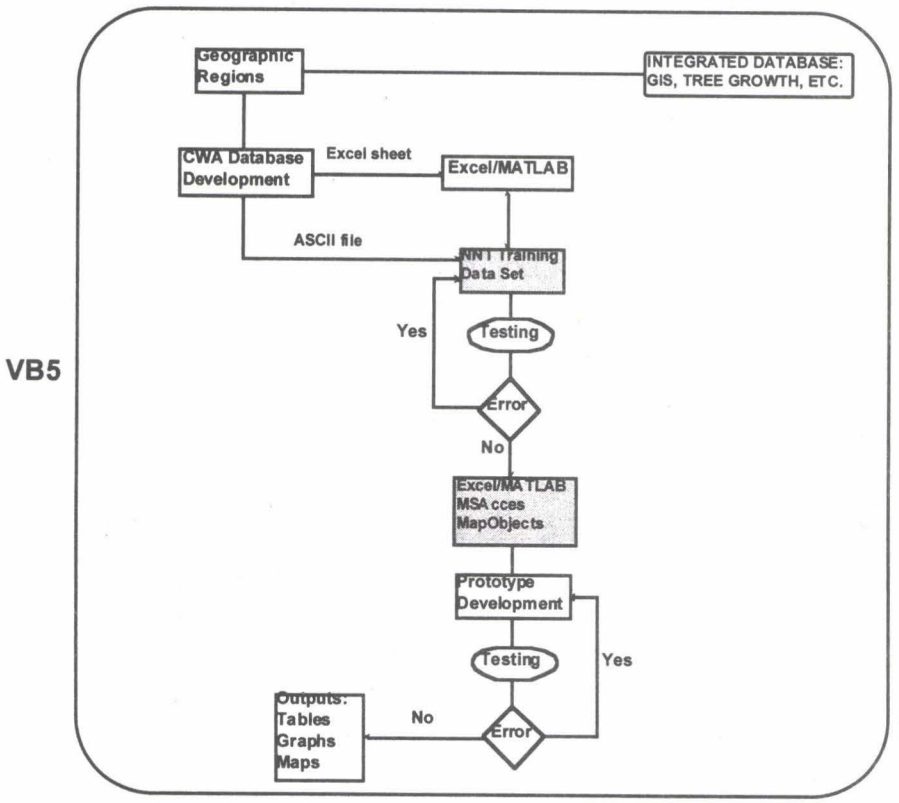


Figure 2.—*Neural Network and Geographic Information System Decision Support System (NNGIS-DSS) communication architecture showing the linkages among various software and data bases within the Forest Fertilization Decision Support System.*

management, analysis, and visualization. This component is still under development.

The system architecture shown in figure 2, exhibits the system functionality that brings effectiveness and achievement between data base and software components. The Visual Basic programming system provides the tools that allow creation and display of easy and robust applications through the development of user friendly graphical user interfaces.

RESULTS

The following sections explain the progress achieved up to now with respect to the main parts of the prototype under development. NNGIS-DSS embodies a set of interactive and structured interfaces that guides one through each module or component. The application design encompasses the standard Windows Application Programming Interface (Win API) environment for easy and simple use. Each modular window contains a set of buttons that perform operations on run time. The first window, which starts the consultation per se, begins by asking the user the geographic area of interest. The window that chooses the IFTNC geographic region for training and simulation is shown in figure 3.

The window (choosing an IFTNC Inland Northwest region for training) consists of nine pieces of information denoting the geographic regions already designed for system functioning and analysis. Each geographic region retains its own input/output attribute values for system training and simulation. There is also an exit button to end the consultation if desired at this point. Central Washington North and South regions use the same data set for training; that is, they poll the Central Washington region data set (see fig. 1). To enter the region of interest, the user places the cursor on a region box and clicks the left mouse button thus activating a window where the attribute data reside to conduct the training. The process is further explained in the following section.

Mathematical

The window (Central Washington NN training) shows the events that begin the network training, system inputs editing from field data collection, and simulated outputs computational process. The window also shows an Excel OLE control, plus two other buttons: Teanaway GIS data base and start a new consultation.

Figure 3.—*The window from the fertilization decision support system that selects the geographic region used to train and simulate the neural network mathematical model.*

The network training process constitutes the following action buttons: the training of the network, the user input box, and run the simulation events that predicts tree growth response. As its name indicates, "the train the network" button triggers the event that places the Excel sheet data into MATLAB matrix format to initiate the neural network learning and training. The "user input box" button, brings in the user's input attribute form that can be modified by entering new input data values to begin the system prediction computation. The "run the simulation" button allows computation of target output values which will then be used in the fertilization decision criteria.

Using an OLE container control, we are able to display and manipulate data from Microsoft Excel spreadsheet. For example, if the user wants to see how the spreadsheet having the data input and output for the Central Washington region is formatted, they can double click on the Excel Cwa icon for a closer look (fig. 4). The flexibility of the application is noted here because the user can edit the worksheet by updating cells as new data are acquired. If new data are gathered that entail new attributes (fields), then re-training the network is recommended; otherwise, if just cell values are changed, re-training is not required. The Excel sheet that exhibits part of the Central Washington region input/output data set is shown in figure 5.

In this module, if the user desires to try a new data set, they can click the "start a new consultation" button that allows access to the window for choosing a geographic region for training.

Visualization Component

The stand location and visualization module is illustrated in this section. Since the Teanaway ecosystem management area data has been used for system evaluation and training demonstration, there is a button that connects directly to the Teanaway GIS data base (fig. 4). However, the system can also open a directory window to look for a desired map layer file. The Teanaway GIS data base was provided by Boise Cascade Corporation. The stand location and visualization process starts once the output result is computed; that is, after a user reports the inputs, a spatial query operation will also select those attributes already elucidated on the dbase table associated with the map layer of interest (fig. 6).

When a user clicks on the Teanaway GIS data base button on the Central Washington NN training window (see fig. 4), it produces the stand-map layer Teanaway ecosystem management study area containing polygon attribute information (see fig. 6, table.dbf).

One important feature of the stand location and visualization procedure is that when the user queries the inputs: longitude and latitude, the x and y points will be located on the map, and this ensures that the data considered are within the study area boundary of interest; that is, site specific. A quick step to start this process is to perform a

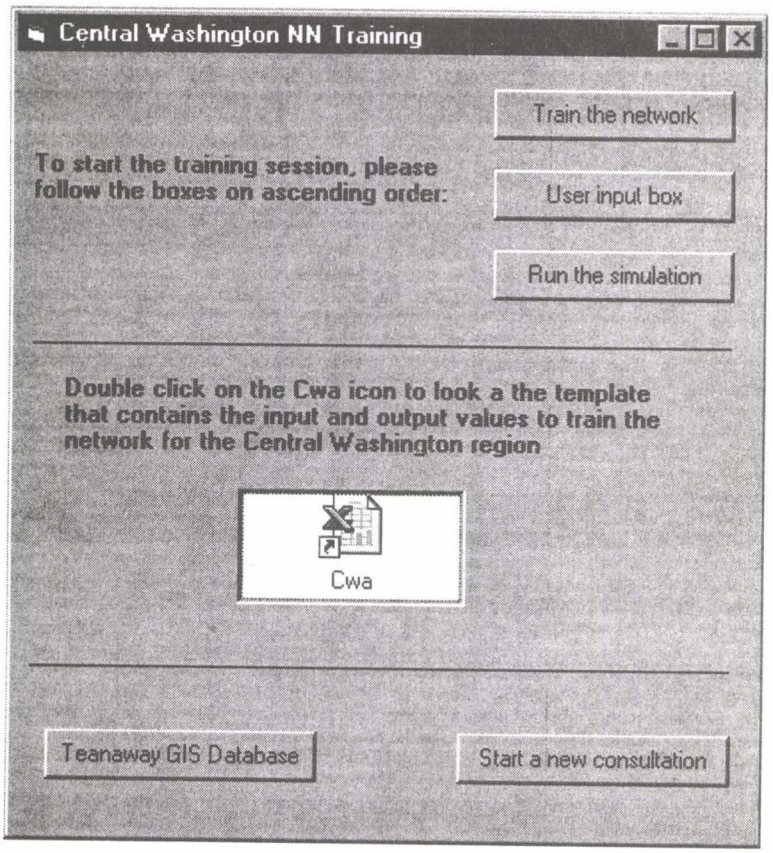

Central Washington NN Training
Train the network
To start the training session, please follow the boxes on ascending order:
User input box
Run the simulation
Double click on the Cwa icon to look a the template that contains the input and output values to train the network for the Central Washington region
Cwa
Teanaway GIS Database
Start a new consultation

Figure 4.—*The window from the fertilization decision support system that shows the Central Washington region input and output data set used to train and simulate the network.*

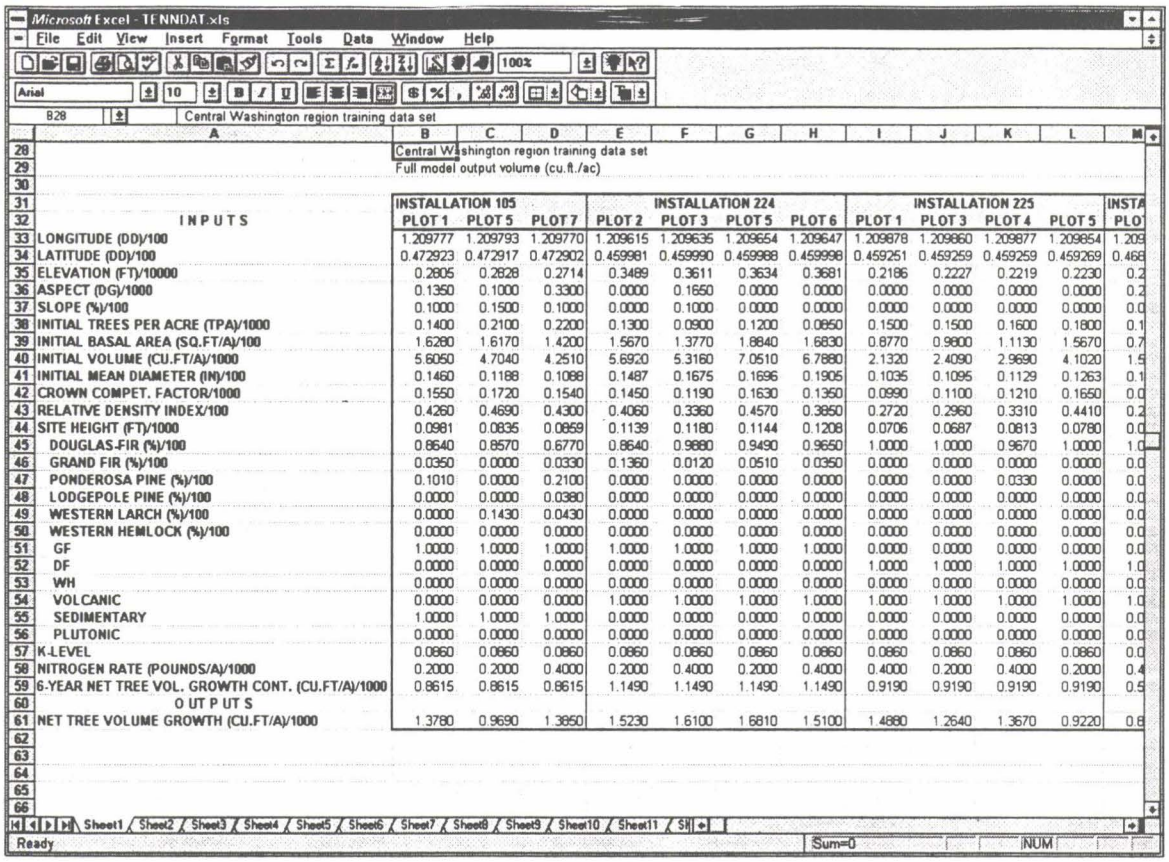
search by distance event in MapObjects as follows: first zoom in the area of interest and by holding the left mouse button move the cursor to any area, then release, and move just the cursor to draw a circle that selects those stands falling into the whole or edge boundaries of the drawn circle (fig. 7).

A spatial analysis enhancement to this procedure involves additional information on a particular stand to prescribe forest fertilization operations, extra information on the surrounding stands in the area of the circle will be available. Thus, the user can extend the search and look at other stands for further assessment and consequently future fertilization decision making. Stands are identified by moving the cursor to any polygon under the circle area, then clicking the right mouse button and then the left to produce a window prompting the user with the name of the feature. For this particular demonstration the program is directed to identify habitat type (fig. 8).

After the spatial query is done, the next step is to combine adjacent stand attribute information with other tables for system reporting and analysis. The relate operation between Table.dbf and Book1.xls will be achieved to capture information on tree growth prediction, and combined with Table1.mdb for operational and logistic actions to conduct forest fertilization. At this point during the consultation process, a multiple criteria priority for stands fertilization operation emerges. For instance, the selected stands will vary in terms of accessibility, silvicultural treatments, stand age, acreage, predicted volume per acre, harvest priorities, and perhaps other restrictions to forest practices that influence the way fertilization operations are conducted. Thus, Tables Book1.xls and Table1, 2, and 3.mdb will serve as input data for further development of the software which includes the fuzzy logic module to cope with these new set of fuzzy questions. The Teanaway stand attribute data triggered by the "Access data base" button on the Teanaway Database window of figure 7 is shown in figure 9.

Outputs

The outputs from the Decision Support System consist of hard copy maps, tables, graphs, and a short report. This



Microsoft Excel - TENNDAT.xls

File Edit View Insert Format Tools Data Window Help

Central Washington region training data set

Central Washington region training data set
Full model output volume (cu.ft./ac)

INPUTS	INSTALLATION 105 PLOT 1	PLOT 5	PLOT 7	INSTALLATION 224 PLOT 2	PLOT 3	PLOT 5	PLOT 6	INSTALLATION 225 PLOT 1	PLOT 3	PLOT 4	PLOT 5	INSTA PLO
LONGITUDE (DD)/100	1.209777	1.209793	1.209770	1.209615	1.209635	1.209654	1.209647	1.209878	1.209860	1.209877	1.209854	1.209
LATITUDE (DD)/100	0.472923	0.472917	0.472902	0.459981	0.459990	0.459988	0.459998	0.459251	0.459259	0.459259	0.459269	0.468
ELEVATION (FT)/10000	0.2805	0.2828	0.2714	0.3489	0.3611	0.3634	0.3681	0.2186	0.2227	0.2219	0.2230	0.2
ASPECT (DG)/1000	0.1350	0.1000	0.3300	0.0000	0.1650	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2
SLOPE (%)/100	0.1000	0.1500	0.1000	0.0000	0.1000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0
INITIAL TREES PER ACRE (TPA)/1000	0.1400	0.2100	0.2200	0.1300	0.0900	0.1200	0.0950	0.1500	0.1500	0.1600	0.1800	0.1
INITIAL BASAL AREA (SQ.FT/A)/100	1.6280	1.6170	1.4200	1.5670	1.3770	1.8840	1.6830	0.8770	0.9800	1.1130	1.5670	0.7
INITIAL VOLUME (CU.FT/A)/1000	5.6050	4.7040	4.2510	5.6920	5.3160	7.0510	6.7880	2.1320	2.4090	2.9690	4.1020	1.9
INITIAL MEAN DIAMETER (IN)/100	0.1460	0.1188	0.1088	0.1487	0.1675	0.1696	0.1905	0.1035	0.1095	0.1129	0.1263	0.1
CROWN COMPET. FACTOR/1000	0.1550	0.1720	0.1540	0.1450	0.1190	0.1630	0.1350	0.0990	0.1100	0.1210	0.1650	0.0
RELATIVE DENSITY INDEX/100	0.4260	0.4690	0.4300	0.4060	0.3360	0.4570	0.3850	0.2720	0.2960	0.3310	0.4410	0.2
SITE HEIGHT (FT)/1000	0.0981	0.0835	0.0859	0.1139	0.1180	0.1144	0.1208	0.0706	0.0687	0.0813	0.0780	0.0
DOUGLAS-FIR (%)/100	0.8640	0.8570	0.6770	0.8640	0.9880	0.9490	0.9650	1.0000	1.0000	0.9670	1.0000	1.0
GRAND FIR (%)/100	0.0350	0.0000	0.0330	0.1360	0.0120	0.0510	0.0350	0.0000	0.0000	0.0000	0.0000	0.0
PONDEROSA PINE (%)/100	0.1010	0.0000	0.2100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0330	0.0000	0.0
LODGEPOLE PINE (%)/100	0.0000	0.0000	0.0380	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0
WESTERN LARCH (%)/100	0.0000	0.1430	0.0430	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0
WESTERN HEMLOCK (%)/100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0
GF	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0
DF	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0
WH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0
VOLCANIC	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0
SEDIMENTARY	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0
PLUTONIC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0
K-LEVEL	0.0860	0.0860	0.0860	0.0860	0.0860	0.0860	0.0860	0.0860	0.0860	0.0860	0.0860	0.0
NITROGEN RATE (POUNDS/A)/1000	0.2000	0.2000	0.4000	0.2000	0.4000	0.2000	0.4000	0.4000	0.2000	0.4000	0.2000	0.4
6-YEAR NET TREE VOL. GROWTH CONT. (CU.FT/A)/1000	0.8615	0.8615	0.8615	1.1490	1.1490	1.1490	1.1490	0.9190	0.9190	0.9190	0.9190	0.5
OUTPUTS												
NET TREE VOLUME GROWTH (CU.FT/A)/1000	1.3780	0.9690	1.3950	1.5230	1.6100	1.6810	1.5100	1.4880	1.2640	1.3670	0.9220	0.8

Sheet1 Sheet2 Sheet3 Sheet4 Sheet5 Sheet6 Sheet7 Sheet8 Sheet9 Sheet10 Sheet11

Ready Sum=0 NUM

Figure 5.—*The Microsoft Excel window from the fertilization decision support system the shows the Central Washington region worksheet input/output data set.*

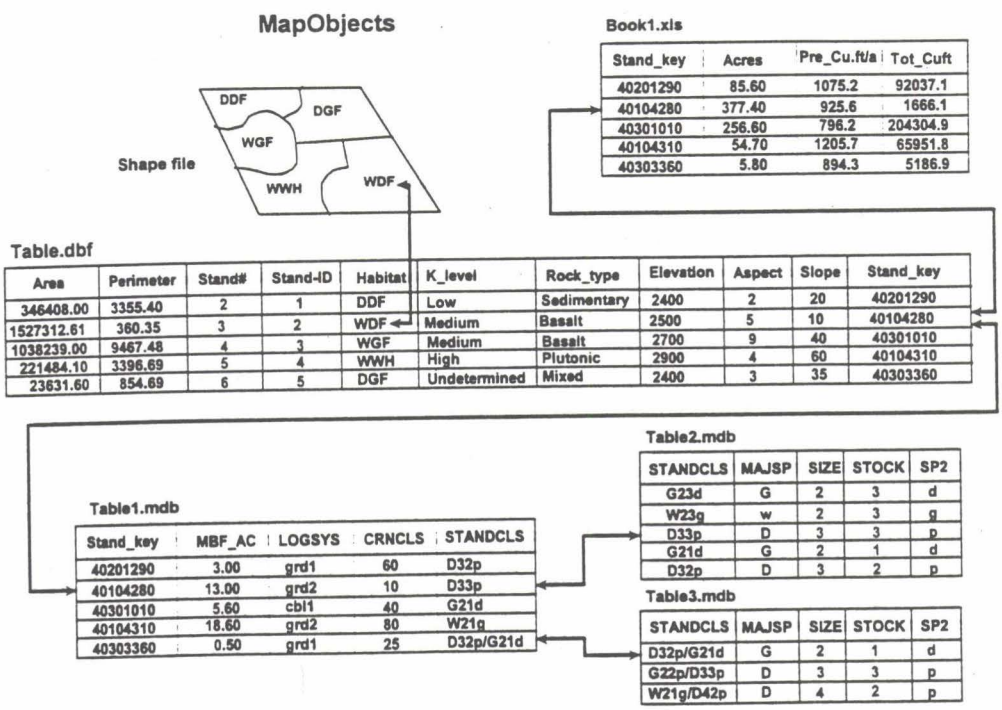
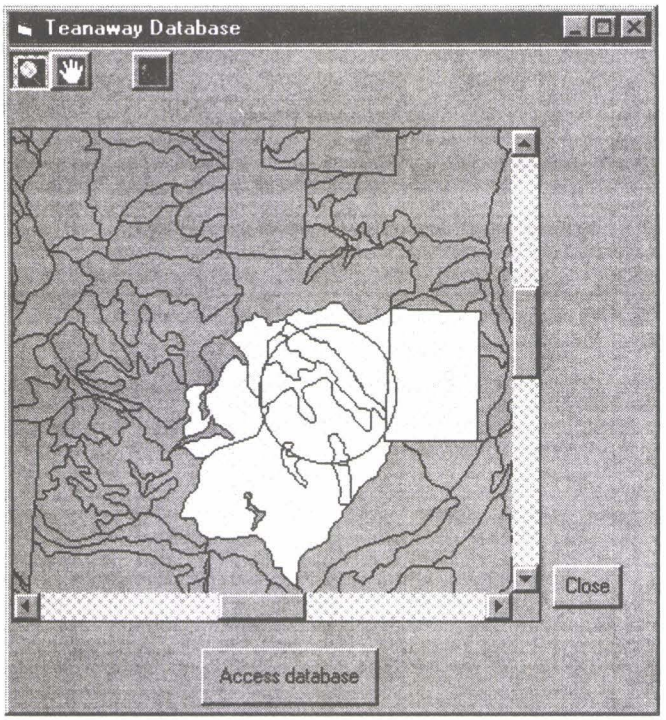

MapObjects
Shape file
DDF
DGF
WGF
WWH
WDF
Book1.xls
Stand_key | Acres | Pre_Cu.ft/a | Tot_Cuft
40201290 | 85.60 | 1075.2 | 92037.1
40104280 | 377.40 | 925.6 | 1666.1
40301010 | 256.60 | 796.2 | 204304.9
40104310 | 54.70 | 1205.7 | 65951.8
40303360 | 5.80 | 894.3 | 5186.9
Table.dbf
Area | Perimeter | Stand# | Stand-ID | Habitat | K_level | Rock_type | Elevation | Aspect | Slope | Stand_key
346408.00 | 3355.40 | 2 | 1 | DDF | Low | Sedimentary | 2400 | 2 | 20 | 40201290
1527312.61 | 360.35 | 3 | 2 | WDF | Medium | Basalt | 2500 | 5 | 10 | 40104280
1038239.00 | 9467.48 | 4 | 3 | WGF | Medium | Basalt | 2700 | 9 | 40 | 40301010
221484.10 | 3396.69 | 5 | 4 | WWH | High | Plutonic | 2900 | 4 | 60 | 40104310
23631.60 | 854.69 | 6 | 5 | DGF | Undetermined | Mixed | 2400 | 3 | 35 | 40303360
Table1.mdb
Stand_key | MBF_AC | LOGSYS | CRNCLS | STANDCLS
40201290 | 3.00 | grd1 | 60 | D32p
40104280 | 13.00 | grd2 | 10 | D33p
40301010 | 5.60 | cbl1 | 40 | G21d
40104310 | 18.60 | grd2 | 80 | W21g
40303360 | 0.50 | grd1 | 25 | D32p/G21d
Table2.mdb
STANDCLS | MAJSP | SIZE | STOCK | SP2
G23d | G | 2 | 3 | d
W23g | w | 2 | 3 | g
D33p | D | 3 | 3 | p
G21d | G | 2 | 1 | d
D32p | D | 3 | 2 | p
Table3.mdb
STANDCLS | MAJSP | SIZE | STOCK | SP2
D32p/G21d | G | 2 | 1 | d
G22p/D33p | D | 3 | 3 | p
W21g/D42p | D | 4 | 2 | p

Figure 6.—*Related operation between an Excel worksheet, data base table, and a table associated with the forestry stand map layer from the fertilization decision support system.*



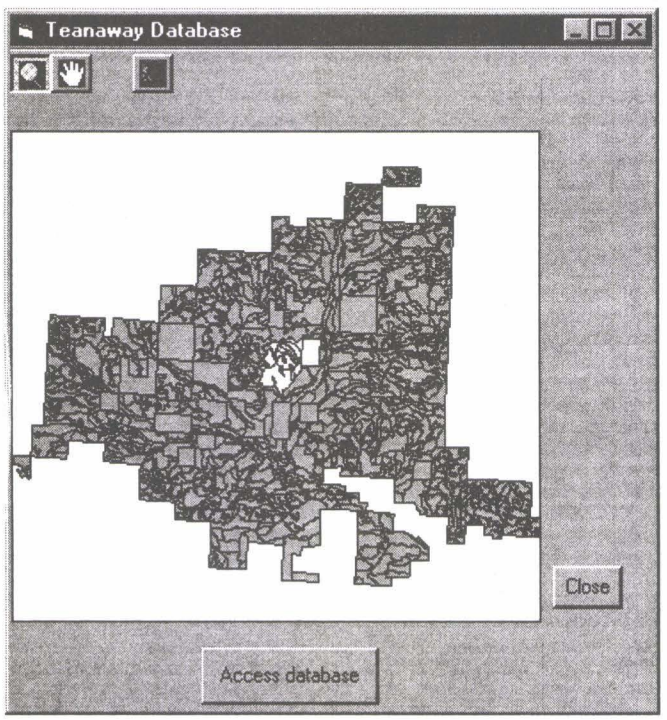


Figure 7.—*The windows from the fertilization decision support system depicting the Teanaway ecosystem management stand layer study area that shows the search by distance operation at a narrow and expanded view.*

Figure 8.—*The identity window from the fertilization decision support system that shows the habitat type attribute elucidated for fertilization decision making.*

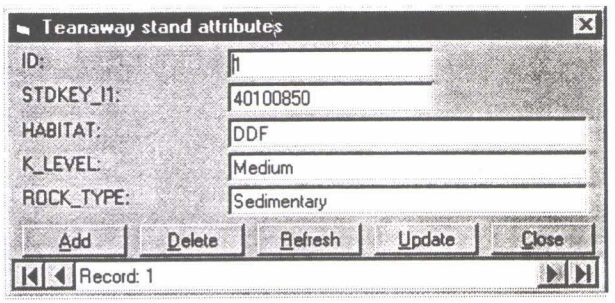


Figure 9.—*The window from the fertilization decision support system that shows the Teanaway ecosystem management area stand attribute data.*

part of the application will help decisionmakers compare different stands elucidated and to conduct a priori judgments for fertilization operations.

CONCLUSIONS

- NNGIS-DSS comprises a powerful and sophisticated information data management and analysis tool that will bring a synergistic relationship between data, maps, and end users.
- It is flexible (can be upgraded and re-trained as new data are acquired), simple, and straight-forward to use under a Microsoft windows environment.
- It uses commercial software available in the market.
- An expansion to this research project will include:
    1. A fuzzy logic module for multiple decision making criteria.
    2. Incorporation of new multirate fertilization treatment data into the input/output data set and re-training of the network.
    3. Testing and validation of the system with real case study data collected from the Teanaway ecosystem management area.
    4. Integration with other DSS such as FORPLAN or FVS

5. Inclusion of on-line documentation to access information on any desired feature of the software.
6. Incorporation of Internet functionality into the application.
7. Distribution of the finished application by creating a .EXE file through a run-time dynamic-link library (DLL).
8. System reporting and documentation.

This demonstration exercise gives a first insight into the automation process to conduct fertilization operations in the Central Washington region. Further software design and development is needed. This or any future enhancement to this application is not intended to replace foresters; on the contrary, it is intended to be used as a supporting tool for decision making bringing an efficient, quick, real time, and state-of-the-art fertilization support instrument in the Inland Northwest.

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KNOWLEDGE-BASED DECISION SUPPORT FOR ENVIRONMENTAL ASSESSMENT

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ABSTRACT.—EMDS is a knowledge-based decision support system for the design and conduct of ecological assessments at any geographic scale. ArcView provides the primary system interface to the EMDS system. The NetWeaver development system incorporated into EMDS provides a knowledge base development environment in which an assessment team assembles a knowledge base that describes the logical relations (dependencies) among topics of interest to an assessment, underlying ecosystem states and processes, and data needed to evaluate topics, states, and processes. The Assessment system includes two subsystems: (1) the Analysis subsystem provides an interface to the knowledge base performing analyses. Knowledge-based reasoning as implemented in the NetWeaver knowledge base engine provides powerful analytical capabilities for environmental assessment; (2) the Data Acquisition Manager uses information about the influence of missing data, and information gathered from the user about the ease of acquiring missing data to prioritize missing data as an aid to planning new data collection to improve an assessment.

INTRODUCTION

The objective of the Ecosystem Management Decision Support (EMDS) project is to improve the quality of environmental assessments and the efficiency with which they are performed. EMDS version 1.0 is an application framework for knowledge-based decision support of environmental assessments that integrates state-of-the-art geographic information system (GIS) and knowledge-based reasoning technologies in the Microsoft Windows® environment to conduct analyses at any geographic scale.[2] We describe the EMDS system as an application framework, in part at least, because it does not come "ready to run out of the box." Instead, the system provides a very general solution method (e.g., a framework) for conducting environmental assessments.

Perhaps sometime in the future, environmental assessment teams will be able to assemble a list of all topics they want to include in an assessment, assemble a list of data requirements needed to address those topics, and find they have all the required data. In the meantime, however, assessments routinely need to deal with incomplete data. There may be some missing observations for several to many data types. There may be no data at all for (possibly many) others.

One solution to the problem of missing data is to tailor the assessment to existing data. However, this is a poor way to conduct an assessment of environmental phenomena with complex inter-relations because it is extremely difficult, if not impossible, in such an approach to infer what is not known about the data that might be relevant to the assessment and how influential omitted data might be for determining observed ecosystem states and processes. Instead, a basic premise underlying the development of the EMDS system is that it is preferable to construct a logical model that reflects our best understanding of how all states and processes relevant to the assessment are inter-related, regardless of whether relevant data are currently available.

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[2]*The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.*

The EMDS inference engine uses a simple algorithm to compute the influence of missing data based on how many states and processes use the information, and at what level the information enters a knowledge base structure. The EMDS system's Data Acquisition Manager component uses information about data influence to assist users with prioritizing new data acquisition needs.

KNOWLEDGE BASE CONCEPTS

Knowledge-based reasoning is a form of knowledge representation in which phenomena are described in terms of abstract entities and their logical relations to one another (Schmoldt and Rauscher 1995). Two basic reasons for using knowledge-based reasoning are:

1. The entities or relations involved in the problem to be solved are inherently abstract so that mathematical models of the problem are difficult or impossible to formulate.
2. A mathematical solution is possible in principle, but current knowledge is too imprecise to formulate an accurate mathematical model.

A knowledge base embodies knowledge about how to solve a problem in some domain of interest. Several different formalisms for knowledge-based representation have been developed over about the last 20 years (Schmoldt and Rauscher 1995). EMDS incorporates the NetWeaver™ knowledge base engine for knowledge-based reasoning (Saunders *et al.* 1989, 1990). This system implements a knowledge base as networks of logical dependencies (Stone *et al.* 1986) which represents knowledge about how to solve a problem (in our case, how to evaluate topics of interest in an assessment) in terms of the topics of interest in the problem domain, and logical relations among these topics.

EMDS DESIGN AND OPERATION

The ArcView®, Assessment, and NetWeaver systems are the three primary subsystems of EMDS (figs. 1 and 2). Communication between ArcView and the Assessment systems in particular is implemented with a dynamic data exchange (DDE) client-server architecture in which ArcView functions as the server application. Reynolds *et al.* (1996) give an indepth account of system design and operation. EMDS version 1.0 provides support for:

- constructing knowledge bases that describe logical relations among ecosystem states and processes of interest in an assessment,
- processing the resulting knowledge base to get a geographic assessment of ecosystem states and processes at the level of landscape features,
- evaluating the influence of missing data,

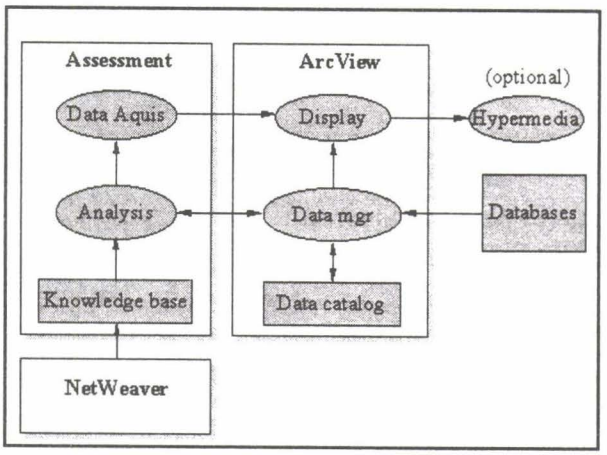

Figure 1.—*Basic architecture of the EMDS system.*

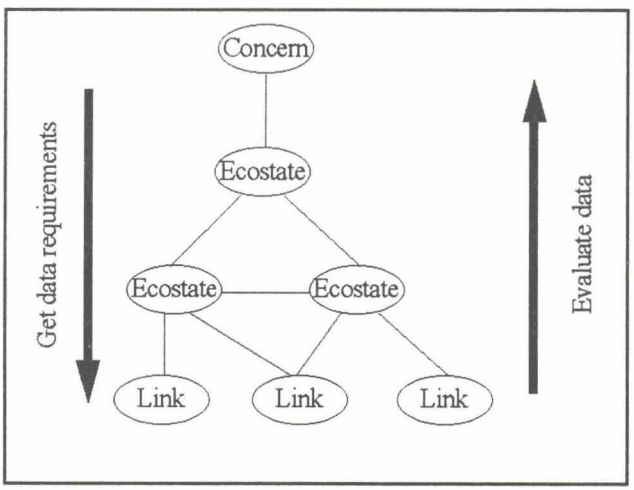

Figure 2.—*NetWeaver knowledge base processing.*

- prioritizing new data acquisition in light of data influence, and
- basic project management.

To conduct an assessment with EMDS, an assessment team:

1. Constructs a data catalog that identifies the sources of all GIS themes that can potentially enter into an assessment.
2. Constructs a knowledge base that describes relations among all ecosystem states and processes of interest to the assessment.
3. Selects topics on which to run an assessment, view results, assess data requirements, and perform what-if scenarios.

EMDS includes components that manage all three activities. The customized ArcView project template in EMDS includes utilities for setting up an EMDS ArcView project, creating and editing the data catalog, and displaying analysis results.

NetWeaver provides the knowledge base development environment. NetWeaver knowledge bases are highly modular. As a consequence, the system lends itself very well to the incremental evolution of knowledge bases in the sense that one can start with a simple initial representation and gradually evolve the knowledge base into a larger, more complex representation in a series of small increments. NetWeaver also fully integrates a complete implementation of fuzzy calculus that overcomes a basic knowledge representation problem of traditional rule-based systems which are inherently bivalent.

Although the EMDS framework approach requires users to build the data catalog and the knowledge base, there are also two significant advantages to a framework solution. Topics to be included in an assessment, relations among ecosystem states and processes in the knowledge base, and sources of data are completely determined by the user, so the user has a very high degree of control over problem specification. Also, assessment applications can be developed somewhat generically for a larger region, and then easily customized for specific subregions.

EMDS OUTPUT

The EMDS Assessment system can display a variety of maps in ArcView after an analysis has been run. Map options include display of network truth values, indicators for absence of data, and influence rank values of missing data. All values are mapped to specific landscape features within their respective GIS themes in the assessment area.

Once the DAM process has been completed for prioritizing data types, several graphs summarizing attributes of missing data also can be displayed in ArcView:

- priority value for data links (synthesis of ease of acquisition and data influence),
- ease of acquisition (supplied by the user in the Data Acquisition Manager),
- influence (computed by the NetWeaver knowledge base engine),
- number of rows (feature records) with influence (for each data type),
- percent of rows with influence (for each data type),
- number of no data values (for each data type), and
- percent of no data values (for each data type).

A data type may have missing data (that is, item 6, number of no data values, is positive), but not have any influence on improving the completeness of an assessment, because the missing data associated with the data type are not relevant given the availability of other data. The inherent ability of NetWeaver to provide this type of information has important implications for improving the efficiency of assessments.

EFFICIENT USE OF THE EMDS FRAMEWORK

The EMDS framework is a flexible environment for designing and performing assessments. It is perfectly acceptable, for example, to conduct an assessment in the conventional way:

1. perform an information needs assessment,
2. acquire the data that has been identified,
3. enter the information in a GIS system,
4. analyze the data, and
5. produce a report.

However, an assessment conducted in the usual manner ignores much of the power inherent in a knowledge-based approach to assessment. The dependency network knowledge base encapsulates important information about inter-relations of topics and data that can be used to improve the efficiency with which an assessment is conducted. Given a knowledge base, the NetWeaver engine automatically generates valuable information about the influence of missing data. This is true even in the extreme case in which there are no data at all.

Because of the size and complexity of ecological assessments, thinking about all the implications of all the relations is virtually impossible even for a room full of technical experts. Although dependency networks can be extremely large, they are incrementally built out of small, simple elements, and can be built fairly quickly. The result of knowledge base construction with networks is, in effect, a road map of the dependencies that the system can use to provide useful information to guide the assessment process. With this in mind, we suggest an alternative model for the assessment process that can achieve significant savings in time, funds, and use of personnel.

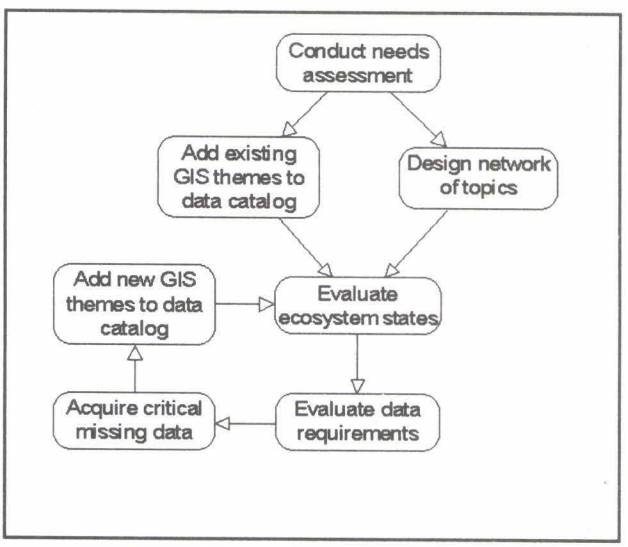
Conduct needs assessment
Add existing GIS themes to data catalog
Design network of topics
Add new GIS themes to data catalog
Evaluate ecosystem states
Acquire critical missing data
Evaluate data requirements

Figure 3.—*Iterative cycle of data acquisition based on evaluation of data influence.*

PRELIMINARY EXPERIENCE WITH EMDS

Beta testing of the system began in December 1996 with a late-version prototype. Field trials are currently being conducted on three multiagency ecoregional assessments in the United States (Northern Great Plains, Great Lakes, and Ozark/Ouachita Highlands Assessments). Although it is too soon to provide a complete evaluation of system performance in these tests, initial results have been very encouraging. Land managers and resource specialists have demonstrated a reasonable level of proficiency in the art and science of knowledge base development with only 1 day of training. Similarly, the basics of system setup and maintenance have been mastered by GIS staff with 3 to 4 hours of training.

DISCUSSION

Information about the influence of missing data can be as important to an assessment as information that can be derived from available data. There are two basic questions about missing data that determine its priority for collection:

- What missing data should be obtained to best improve completeness of an assessment (considering their influence)?
- How easy is it to obtain the missing data?

The EMDS inference engine automatically answers the first question in the course of processing a knowledge base. The EMDS Data Acquisition Manager determines the priority of missing data by synthesizing a priority score from each data type's influence score and a measure of its "ease of acquisition."

Data requirements associated with assessments often make the process expensive, time consuming, and labor intensive. The EMDS system has the potential to significantly improve the efficiency of an assessment process by identifying data that are no longer important by virtue of being redundant to, or rendered irrelevant by, information that is already available. The cost associated with this benefit is, of course, that one must first construct a knowledge base, which itself requires time and effort. However, we believe that managers conducting assessments will find the investment in constructing a formal logical inferencing model yields returns in time and effort saved that substantially outweigh the investment in knowledge base development.

EMDS allows construction and evaluation of arbitrarily large knowledge bases that can process attribute data from a diverse collection of landscape features within a single analysis, making it relatively easy to integrate many different types of concerns into an analysis, and account for their inter-relations, at least to the extent that we can understand and represent them symbolically.

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METADATA STANDARDS FOR FORESTRY AND NATURAL RESOURCES

M.H. Pelkki and G.J. Arthaud[1]

ABSTRACT.—Metadata are, in their most basic sense, data about data. Metadata compose the descriptions about data that make that data useful. This paper describes the need for metadata in both spatial and attribute data bases. Current metadata standards are presented and their effects on forestry and natural resource information systems are discussed. The development of additional forestry and natural resource related metadata standards are then discussed with particular emphasis on incorporation of variance/error metadata, temporal metadata, and metadata to describe processes as well as states of the real world.

INTRODUCTION

What are Metadata?

Metadata are, in the simplest sense, data about data (Everest 1986). They describe data in a data base, defining content, scale, units of measurement, defining coded values, providing quality control information and explaining what purposes the data are used. In a very real sense, metadata make data useful. For example, in a forest inventory data base, an attribute of a forest stand might be called BASAL AREA. In one instance of a stand, the value recorded for this attribute is "117." Metadata are needed to determine if the basal area is in square feet per acre, square meters per hectare, if the units are whole numbers of tenths, if the basal area pertains to only overstory trees or only to woody stems with a particular diameter limit. In fact, the data item itself is small relative to the metadata needed to correctly use the data. Ganter (1993) states that metadata answer two fundamental questions about data:

(1) What are the data and do they meet our needs?
(2) How have the data been changed and what new data have been derived?

Ganter's first question covers the traditional, primary function of metadata, describing the current status of the data. But the second question moves metadata beyond a single snapshot of the data and into the realm of temporal data management and the concepts of raw or source data and derived or processed data.

Metadata are not only important for using data correctly, but it is also important when data is to be shared with multiple users. Curtice (1986) stated that the promise of data bases is their ability to share timely and consistent data and to leverage existing data collection and storage against unanticipated, future requests for data. But all too often data do not conform to any standards and the semantics of data are buried in the data base management system schema, application programs, users' and developers' minds (Boulanger and March 1989). This has led to growing stockpiles of stand alone data bases with inconsistent data, single purpose projects and data bases that waste information management resources and result in inconsistent analyses (Hofmeyr *et al.* 1991). It leads to inconsistent application of data, users apply different definitions and standards to data at their choosing. And it also means that important metadata leaves the system when data base developers are no longer available to provide metadata unrecorded by the system.

Obviously, metadata are important and though not a lot of thought has been given to metadata, its presence and frequency are increasing as more data bases are viewed as shared corporate assets. As metadata become an integral part of data bases, standards are needed to ensure a consistent, minimal set of metadata knowledge maintained for all data bases. Everest (1986) suggests that metadata should be available and managed via the same data base management systems as the actual data. Any data not maintained by the data base management system must be maintained by humans and as stated above, this leads to unsatisfactory data quality. Developing standards for spatial metadata has been a focus of the Federal Geographic Data Committee (FGDC) for several years in the 1990's (Tosta 1992, 1994). And while individual corporations and public agencies have data and metadata recommendations or standards, few spatial data bases conform to these standards. And national standards for attribute data in forestry and natural resources have yet to be addressed.

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The remainder of this paper will present three levels or general types of metadata. These metadata classes can be defined as directory-level, quality and accuracy report, and data dictionary. Examples of these will be provided below. Commonalities among these metadata will be noted and minimal metadata standards for forestry will be suggested.

EXAMPLES OF FORESTRY METADATA

Two examples of directory-level metadata will be presented. The first is a directory of data bases published by the Kentucky Cabinet for Natural Resources and Environmental Protection (Carey 1996). The second is metadata required by the FGDC (University of Texas 1995). Data-dictionary level metadata for the Eastwide (Hansen *et al.* 1992) and Westwide (Woudenberg and Farrenkopt 1995) Forest Inventory Data bases and FGDC-compliant metadata standards will conclude the presentation of examples.

Summary of Data Bases: Natural Resources and the Environment in Kentucky

Kentucky State Regulations (KSR 61.940) requires that the state provide and make accessible an index of all state data bases. From this, the Summary of Databases: Natural Resources and the Environment in Kentucky was published and distributed in 1996. This paper index is a directory of data bases with each metadata field being a variable-length text field. Table 1 lists the metadata schema for this data base. None of the metadata attributes are defined, and the description of each data bases' attributes is limited to their system name, with no definition of individual attributes. The only possible quality attribute is "Integrity," and while it is listed as either "Good" or "Excellent," the meaning is never defined. Also, there are no temporal metadata. Knowing when the data base was created, last updated, or the frequency of updates would be very useful. While this is very rudimentary metadata, it is still very useful.

Minimum Metadata Required by FGDC Spatial Metadata Standard

The FGDC has developed national standards for spatial metadata to assist in data sharing and coordination. There are 10 main sections of FGDC metadata:

1. Identification Information
2. Data Quality Information
3. Spatial Data Organization Information
4. Spatial Reference Information
5. Entity and Attribute Information
6. Distribution Information
7. Metadata Reference Information
8. Citation Information
9. Time Period of Content Information
10. Contact Information

From this list, the directory-level information can be found in items 1, 7, 8, 9, and 10, above. A detailed listing of the minimum directory-level metadata is shown in tables 2 and 3. Note that this metadata provides for changing metadata standards and is quite detailed compared to the Summary of Kentucky Natural Resource and Environmental Databases.

Metadata Provided by Eastwide and Westwide Forest Inventory Data bases

Perhaps the most widely used forest inventory data bases are the Eastwide and Westwide Forest Inventory data-bases developed by the USDA Forest Service, Forest Inventory and Analysis Unit. The documentation for these two data bases (Hansen *et al.* 1992, Woudenberg and Farrenkopt 1995) provides data dictionary-level metadata. However, in the narrative, general quality level information is provided when the data is used on a statewide basis and cautionary statements are provided concerning data quality when subdividing the data into smaller geographic units. Table 4 provides a listing of the metadata recorded for these data bases.

Table 1.—*Metadata for Kentucky natural resource and environmental data bases*

1. Name of data base	8. Contact name	15. Descriptors/Keywords
2. System name of data base	9. Contact address	16. Parameters (attributes)
3. Purpose of data base	10. Contact phone	17. Forms
4. Agency of administration	11. Host computer	18. Sources
5. Department	12. Language	19. Comments
6. Division	13. Coverage	
7. Branch	14. Integrity	

This is fairly typical of metadata for published data bases and is really the minimum metadata for sharing the data. However, it tells us little to nothing about the data. Individual measures of data quality are absent, as are acceptable ranges for data values. The data-dictionary metadata should provide users and managers with information that helps them manage the data base by identifying values that are out of range or incorrectly measured, and it should give the user some idea of data quality.

Data-Dictionary Metadata Required by the FGDC Spatial Metadata Standard

Contrast the data-dictionary for the FIA data (table 4) with that required for entities and attributes in the FGDC Spatial Metadata standard (table 5). Information on attribute domain (the valid set of values for an attribute) is greatly expanded, and there is provision for data quality as well. Source information is also provided for definitions and codesets and providing easier linkages among datasets by identifying sources of definitions for metadata. And also important are the temporal metadata, which provide the user with data currency information.

Table 2.—*Minimum identification information for FGDC compliant spatial metadata*

1 Citation:
Citation_Information:
Originator:
Publication_Date:
Title:
2 Description
Abstract:
Purpose:
3 Time_Period_of_Content:
Time_Period_Information:
Single_Date/Time:
Calendar_Date:
Currentness_Reference:
4 Status:
Progress:
Maintenance_and_Update_Frequency:
5 Spatial_Domain:
Bounding_Coordinates
6 Keywords:
Theme:
Theme_Keyword_Thesaurus:
Theme_Keyword:
7 Access_Constraints:
8 Use_Constraints:

Table 3.—*Minimum metadata information for FGDC compliant metadata*

Metadata_Date:
Metadata_Content:
Content_Information:
Contact_Organization_Primary:
Contact_Organization:
Contact_Address:
Address_Type:
Address:
City:
State_or_Province:
Postal_Code:
Contact_Voice_Telephone:
Metadata_Standard_Name:
Metadata_Standard_Version:

Table 4.—*Metadata for Eastwide and Westwide forest inventory data bases*

1 Structure of record (County, Plot, or Tree)
2 Attribute name
3 Computer alias
4 Column position
5 Format
6 Unit of measure
7 Frequency/restriction (attribute required or not)
8 Key field (yes or no)

WHERE DO WE GO FROM HERE?

We rely daily upon all kinds of information system standards. Hardware and software standards allow us to run operating systems and application software on numerous machines with high degrees of confidence. Processing and application standards allow data to be shared and we can be assured of consistent results. Likewise, metadata standards will improve our ability to exchange data, provide relevant and current data, and enhance our data access. The problem with metadata isn't that researchers and practitioners don't find it useful. The problem with metadata is that, like documenting software, it takes time and effort to do it right! Tables 2, 3, and 5 portray only a portion of the FGDC Spatial Metadata Standard and this metadata alone would pose a significant burden on data base developers. In some cases, the metadata could require more storage and management effort than the data themselves! To manage this problem, the following metadata management suggestions are provided:

Table 5.—*Data-dictionary metadata for FGDC-compliant spatial metadata for entity a nd attribute information*

- 1 Detailed Description
  - Entity type
    - Entity type label
    - Entity type definition
    - Entity type definition source
  - Attribute type
    - Attribute label
    - Attribute definition
    - Attribute definition source
    - Attribute domain values
      - Enumerated domain
        - Enumerated domain values
        - Enumerated domain value definitions
        - Enumerated domain value definition sources
      - Range domain
        - Range domain minimum
        - Range domain maximum
      - Codeset domain
        - Codeset name
        - Codeset source
      - Unrepresentable domain
    - Attribute units of measurement
    - Attribute measurement resolution
    - Beginning date of attribute values
    - Ending data of attribute values
    - Attribute value accuracy information
      - Attribute value accuracy
      - Attribute value accuracy explanation
    - Attribute measurement frequency
- 2 Overview description
  - Entity and attribute overview
  - Entity and attribute detail citation

Maintain directory-level metadata. Research units, companies, government agencies should maintain a directory of data bases and for those data bases the metadata should describe those attributes found in table 1 and also metadata concerning date of collection, a temporal range of when the data are valid descriptions of the real world, how frequently the data are used, and some global indication of data accuracy and quality. Organizations that know what data they have, who manages it, and how to access it can share data more easily within the organization and can provide data-directories to cooperating organizations as well.

All metadata should be maintained using a data base management system. Many directory level data bases are maintained on word processors rather than on data base management systems (DBMS). The metadata should be maintained on the same DBMS as the actual data, as many DBMS can use metadata to assist in managing data. For example, metadata concerning valid domains for a data field are used to error-check a data base as well as inform potential users about the range of values found in the reality represented by the data base.

Identify which data bases are truly corporate and expand their metadata. Almost everyone builds data bases. But only those data bases that are shared or have great potential for sharing are worth the effort of expanding from directory-level to data dictionary-level. How do you identify such data bases? Some features may include: (1) a large number of requests for use by second or third parties, (2) cost of development (expensive data is worth documenting), (3) wide geographic extent, and, (4) generalized nature of data (data bases that support many functions within an organization).

Build from directory-level to data-dictionary level metadata. It is likely that data-dictionaries exist, either explicitly or buried in application programs, DBMS attribute definitions, or users and developers minds. Established directory level metadata will increase the reuse of data bases and build impetus for creating and maintaining detailed on-line data dictionaries.

The name of the game with metadata is leveraging data assets by assisting users in finding data, assuring them of the currency and quality of that data, and providing means of integrating data from various sources into a new data base that is used for purposes unforeseen by the original data base developers.

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INTEGRATING GIS DATA INTO A CHOICE EXPERIMENT OF PREFERENCES OVER RESOURCE USE ALTERNATIVES: A BRITISH COLUMBIA EXAMPLE

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ABSTRACT.—A valley in the Selkirk Mountains of British Columbia was used as the setting for a choice experiment to determine resource values and individual preferences over management alternatives. GIS and management models of wildlife, recreation, and timber already existed from previous research and lent themselves readily to application within a choice modeling framework for valuation and utility analysis. Choice models are a subset of stated preference modeling which have historically been applied to consumer problems. They are now emerging as an alternative to the more conventional valuation approaches such as contingent valuation. This study applies these techniques directly to a specific resource setting and using the spatially referenced detail available through GIS, communicates a great deal of resource information to survey respondents for their evaluation in a choice experiment format. The results of the survey allow inferences on preferences, valuation, trade offs and opportunity costs to be drawn. These are all extremely useful results for resource managers and policymakers alike. This study can serve as an example for larger scale research of this type.

INTRODUCTION

The measurement and valuation of benefits which are nonmarket in nature has perplexed economists and policymakers alike. Because these goods and services are provided and consumed without a transaction occurring in the marketplace, there is no observable market event from which value may be directly assessed. The traditional approach to the nonmarket benefit problem has been to estimate consumer surplus using compensating and equivalent variation concepts on Hicksian demand curves. The most widely used method in this regard has been the contingent valuation method or CVM.

Another approach is to explore the choice process employed by individuals in decisionmaking. Consumers regularly evaluate the benefits attained from various goods and make their choices based on these evaluations. Although this behavior is most observable for choices of consumer goods made in the marketplace, the decision process itself and its connection to preferences and utility are applicable to nonmarket choices and public goods as well.

A significant distinction between the two aforementioned approaches has to do with the manner in which individual preferences are obtained. The contingent valuation methods are direct in the manner in which they determine preferences. Consumers are asked to reveal their preferences in the form of responses to hypothetical situations (willingness to pay for a day of fishing for example). Consumer choice theory uses indirect methods to determine preferences (the travel cost model is an example of an indirect method). The distinction between the direct and indirect methodologies is also described as the difference between revealed and stated preferences in the literature.

Revealed and Stated Preference Methods of Valuation

Revealed preference (RP) methods elicit valuation responses through indirect means. Observations of actual consumer behavior can provide revealed preference results. The method is indirect in that it relies upon the choices a consumer is faced with to define its decision space and simply observes the choices made. These methods do not depend on the direct information about prices and quantities that economists would rather use where available to value goods and services (Bishop and Heberlein 1979). RP methods are applied to extra-market goods and services, (normally associated with natural

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resource problems) because of their ability to determine value without price and quantity information

Stated preference (SP) valuation methods are related to revealed preference methods through their use of random utility modeling (RUM). By asking consumers questions about their preferences, inferences about individual utility can be drawn. Similarly, by observing consumer behavior using indirect methods such as the travel cost method, utility may be assessed in terms of the choices made. Indirect utility functions are at the core of Random Utility Model.

Choice Experiments

A group of SP approaches, called conjoint analysis have been in widespread use in consumer product research but have only recently been applied to resource valuation problems (Coyne and Adamowicz 1992, Adamowicz *et al.* 1994). Conjoint analysis refers to an ensemble of methods used to estimate characteristic utilities based on subjects' responses to combinations of multiple attributes or characteristics. The facility to arrange these multiple decision attributes into a wide range of combinations distinguish this methodology from other SP techniques. Common to all conjoint methods are algebraic models representing human judgment processes and an ability to test these models to determine which methods correctly represent preferences. Experimental choice analysis is a methodology among the approaches used in conjoint analysis. Probabilistic choice models are based on random or constant utility theory and are derived from assumptions about individuals' evaluations of choice objects. Choice experiments (CE) are used to survey individuals and aggregate their preferences into a relatively few (or single) models describing individual choices. This method shares some features with the RP and SP techniques used in resource valuation. As in the case of hedonic pricing methods there is use of individual resource characteristics (attributes) in valuation and as with contingent valuation, hypothetical situations are presented to respondents allowing a wide variety of possible resource combinations to be considered.

Choice experiment methods employ an attribute based approach to determine utility and ultimately value. As with CVM, choice experiments gather utility information directly from consumers, however, the methods differ in the number of resource descriptions they are able to represent. Typical problems associated with CVM are avoided with CE. Embedding effects are addressed directly in CE by having respondents implicitly value components (attributes) (Adamowicz 1994). Yea-saying is avoided in CE because respondents are presented with a wide variety of variously configured alternatives rather than a base case - improved case pairing and would have greater difficulty isolating the "good cause" which generally triggers this form of strategic behavior.

Although CV analyses dominate much of the literature and compensatory judgments, further justification for the use of a choice experiment approach comes from the debate surrounding natural resource damage assessment. Jones and Pease (1995) have argued for the notion of compensating goods to mitigate resource damages. This method has been touted for its avoidance of thorny funding and monetary disbursement issues, however, it is dependent on an attribute based approach in order to measure the amounts of other goods to be used as compensation. Consequently, choice experiment based approaches hold great promise in assessment of compensating goods cases.

Welfare analysis is also possible within the context of choice experiments. Modeling varying levels of resource attributes is the primary purpose of the choice set respondents (consumers) face. Connecting the different attribute levels to monetary changes provides the opportunity to extract welfare measures from the choice experiment results. The methodology has evolved from the compensating variation welfare values extracted from travel cost data, first demonstrated by Hanemann (1984), and later applied to choice experiment data (Coyne and Adamowicz 1992).

Choice experiments are also readily combined with other attribute descriptive technologies such as GIS (geographic information systems). The body of literature integrating GIS with multi-attribute choice experiments is just beginning to emerge, however, the use of visual representations have been suggested and applied in marketing research and in natural resource cases. Thus, the use of a visual medium, such as GIS, is a logical step in the representation of resource attributes. The emergence of accessible GIS technology has only recently become widespread enough that it can readily be considered for integration with choice experiment methods. GIS provides the opportunity to manipulate the attributes which describe the resource effortlessly within the digital environment. This allows simulation of a wide variety of attribute combinations in a visual, spatially referenced format. These simulations would be impossible to implement in reality but can be presented within a choice experiment survey. The ever increasing levels of resource conflict, driven by resource scarcity, also justify the use of spatial modeling tools such as GIS. The ability to represent multiple attributes and multiple uses as GIS overlays allows conflicts and potential conflicts over resources to be directly observed. Improved understanding of how various resource attributes interact and fall into discord improves the ability to understand more exactly that from which value is derived and further provides the means to reduce conflicts over resources and their use.

The advantages of an attribute based method such as choice experiments have been stated above (as have the positive effects of visual representations in valuation surveys). It is a logical conclusion then that a choice experiment of forest resource values supported by GIS information should provide meaningful utility and value results. Upon this foundation it is then possible to begin to identify a suitable forest resource for analysis, one for which there exits some GIS model support, and a suitable survey sample from which utility and value may be assessed.

THE STUDY AREA

The Department of Resource Management and Environmental Studies and the FEPA Research Unit at the University of British Columbia (UBC) have developed a digital resource database for the Tangier Watershed located in the Selkirk Mountains of eastern British Columbia. The aforementioned groups have produced a number of reports on the research covering this valley and the development of the GIS models describing it. Various other agencies such as Parks Canada, BC Hydro, BC Ministry of Forests and BC Ministry of Environment have had involvement in the study of this area. The research effort to produce a GIS model of activities and resources of the Tangier valley is most completely reported in the hypertext document titled "A GIS Approach to Multi-Resource Conflict" by Brown *et al.* in 1995. This is the final report of a series funded by BC Hydro and the Canadian Forest Service which summarizes the GIS modeling results and the multiple resource accounting and trade off analysis as applied to the Tangier valley. This report provided much of the physical resource information used to develop the choice experiment and many of the attributes and levels used. This report was also made available to survey respondents as part of the background provided in the choice experiment.

The Tangier Watershed covers almost 29,000 hectares of alpine and subalpine forest and is surrounded by two National Parks. The area has significant recreational, wildlife, and timber values (some of which are in conflict) and is well suited to be a case study for this type of analysis.

The GIS data base includes topography, hydrology, and forest cover. In addition to the forest cover and harvesting models, there are detailed models of wildlife habitat and recreational use. Habitats have been mapped and modeled for Mountain Caribou and Pine Marten. Heli-skiing use in the Watershed has been mapped and referenced with skier survey data. These research efforts provide a unique opportunity to apply a broad spectrum of forest resource uses in a spatial format and communicate multiple use issues in a very effective manner. Six attributes have been identified for analysis in the choice experiment. Of these attributes, five are resource attributes: timber, caribou, pine marten, heli-skiing, and backcountry skiing. The sixth attribute is a tax/compensation variable which enables monetary valuation and welfare analysis.

The survey methodology used in this analysis employs a choice experiment format. Since the harvest values are already known, and the wildlife models already integrated into the GIS maps these features can be explicitly (graphically) offered as part of the survey. It is possible to survey individual responses to combinations of attributes and determine their utility and thereby infer value from the results. Applying the GIS technology to ascertain nontimber benefit and preference information allows explicit evaluation of the trade-offs between uses and the measurement, in more tangible economic terms, of these trade-offs. Thus, it is possible to assess the opportunity cost of maintaining or enhancing a particular nontimber resource attribute and weigh this (opportunity cost) against the demand for the nontimber value in question.

EXPERIMENTAL METHOD

The random utility model is applied to develop probabilistic choice results among alternatives and their attributes. The utility, V, of alternative i for individual n is expressed as:

$$(1)\quad V_{in} = V(Q_{in}, S_n)$$

Where Q is a vector of attributes and S is a vector of individual characteristics. Utility, V, is modeled as a random variable and is the sum of the observable and unobservable components of total utility. A random utility model gives the probability with which alternatives are chosen. Thus, the probability that the individual chooses alternative i is equivalent to the probability that the utility of alternative i is greater than the utilities of the other alternatives in the choice set.

$$(2)\quad P(i|C) = P(v_{in} + ?_{in} > v_{jn} + ?_{jn}, \text{ for all } j \neq i, j \in C_n)$$

The probability function, $P(i|C)$, is a complicated function of the attributes which has no closed analytic form and may be difficult to compute. It is therefore necessary to make assumptions regarding the form of the probability function in order to facilitate estimation. The most widely applied of these estimators is the multinomial logit form (Maddala 1983):

$$(3)\quad P(i|C) = \exp^{v}in / \Sigma_{j \in Cn} \exp^{v}jn$$

where $P(i|C)$ is the probability that alternative a will be selected from the choice set C. The v's denote scale values or strict utilities which summarize the desirability of alternatives.

Estimation of MNL choice models is accomplished through several methods. The most commonly applied is the log likelihood estimation technique which was used in this experiment.

Once the utilities of the attributes have been estimated it is possible to estimate the welfare effects associated with a change in resource quality. The usual compensating variation expression is presented in Equation 4. However, this is ordinarily applied to recreational site choice, where there are a number of competing sites or states from which to choose and which continue to exist regardless of the choice made. Consequently, Equation 4 contains summations of the utilities of the various sites.

$$(4)\quad CV = 1/\alpha \left({}_{\ln} \Sigma_{i \epsilon Cn} \exp {}^{v n0} - \ln \Sigma_{i \epsilon Cn} \exp {}^{v n1} \right)$$

However, when the objective is to compare only two states of the resource, as it is in this case, this expression reduces to:

$$(5)\quad CV = (1/\alpha)\,(vn0 - vn1)$$

Thus, the compensating variation expression reduces to a utility difference divided by the marginal utility of income (α). The inclusion of a monetary variable in the choice set makes this coefficient readily available and permits calculation of a welfare sum associated with a resource quality change. These values can then be compared with those obtained using other methods such as CVM and assist policy decisions.

In addition to the choice experiment a 10 question contingent valuation survey was included in the experiment to provide comparative results.

The choice experiment utilized a partial factorial, main effects design which evaluated a six attribute, three level choice experiment. The result was a series of 18 response cards listing different combinations of the levels of the six attributes. Each choice response card offers two combinations of the six attributes as well as the status quo. Thus, respondents have the choice of two alternatives or leaving things as they are (status quo).

ESTIMATION AND RESULTS

The choice experiment and CVM survey were administered to a sample of 54 resource professionals living and working in the greater Vancouver area in 1995. The stated preference data obtained from the choice experiment were analyzed using multinomial logit modeling techniques applied through the LIMDEP (Greene 1995) software package. Several variations of the logit model were constructed and analyzed. Effects coding was also applied to the data; however, models with all attributes specified in effects coded format violated the rank condition and were not solvable in LIMDEP. When the effects coding scheme was applied to the data, collinearity between some of the dependent variables became apparent. The resulting models were not solvable due to the creation of a singular determinant matrix which prevents estimation of the least squares estimator (which must be non singular), thereby violating the rank condition. When the attributes are left in the format used in the survey (where the data are continuous), the model achieves solution. A linear form of the model was specified and solved using continuous data. A model specified with effects coded variables for caribou and heli-skiing was successfully run, however; the addition of any of the remaining attributes in effects coded form resulted in the violation of the rank condition. A quadratic form of the model was also specified and solved in LIMDEP. Quadratic forms have been used to model utility in choice experiments (Pekelman and Sen 1979) and have shown superior results to linear specifications.

Generally, the coefficients in all of the models are significant and behave as expected. In all cases the coefficients on the tax attribute have the expected negative sign. The intercept term is insignificant in all but the case of the effects coded model.

Utility for the individual attributes can be inferred directly from their coefficients. The coefficient for the attribute is the marginal utility of that attribute. Determining the utility at various attribute levels is accomplished by multiplying the various levels by their marginal utilities (this applies in the case of the linear and quadratic models). The utility curves for the various attributes are displayed in figures 1-5.

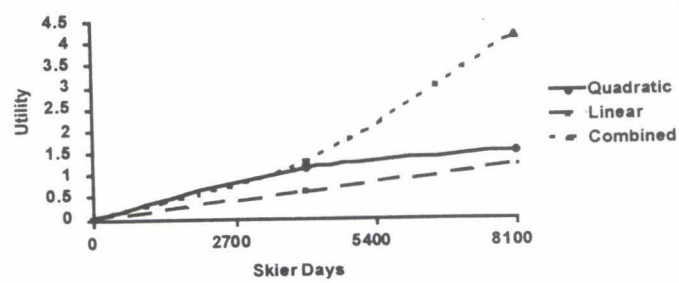

Figure 1.—*Heli-skiing utility curves.*

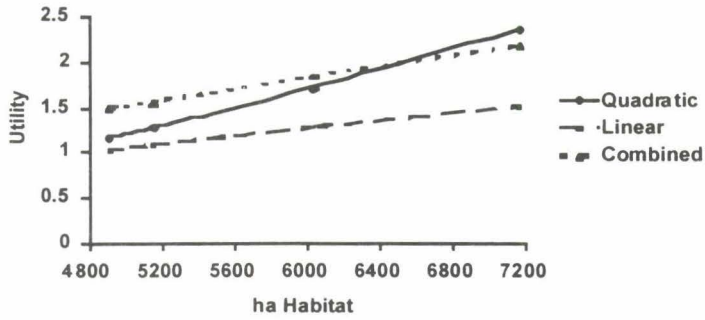

Figure 2.—*Pine marten utility curves.*

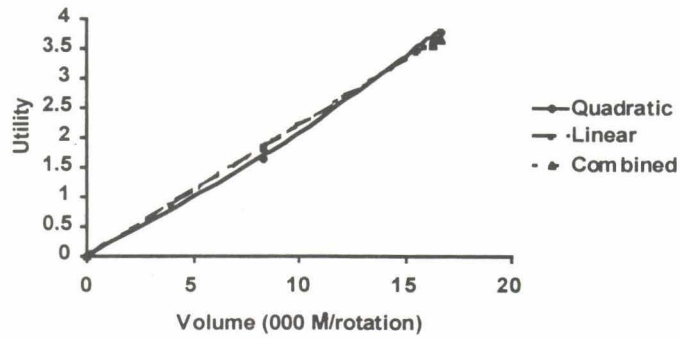

Figure 3.—*Timber utility curves.*

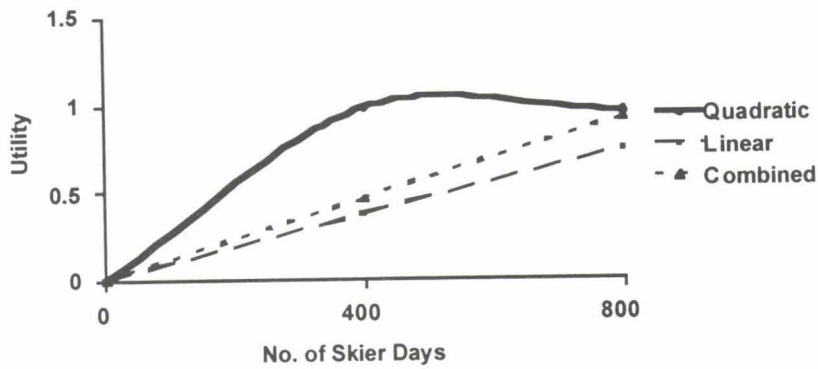

Figure 4.—*Backcountry skiing utility.*

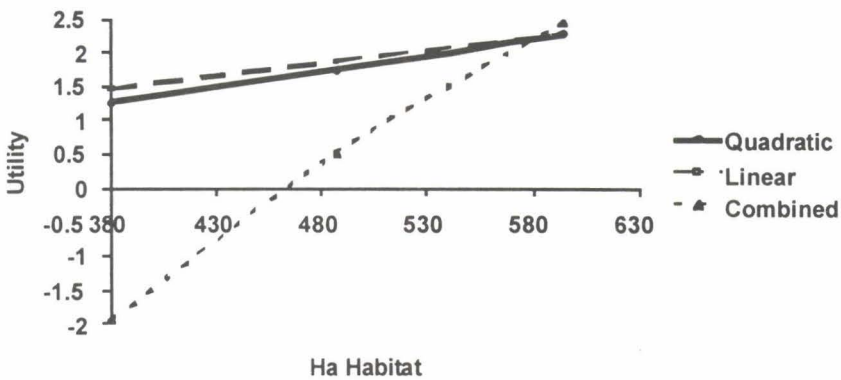

Figure 5.—*Caribou utility curves.*

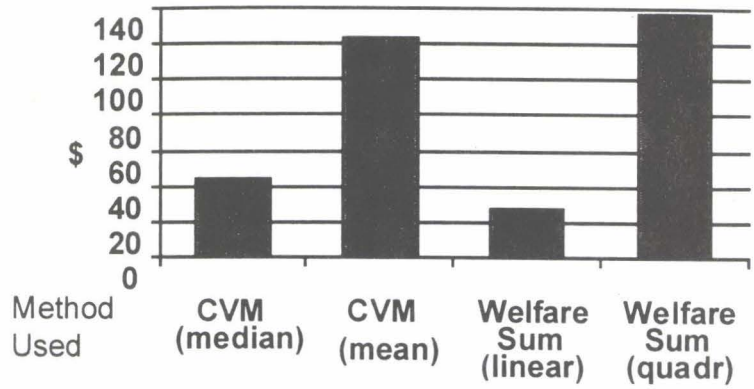

Figure 6.—*Comparing choice experiment and CV results: the value of attribute enhancement.*

DISCUSSION AND CONCLUSIONS

The sample surveyed for this analysis was small and the results certainly reflect the similarity of respondents occupations. However, this does not diminish the usefulness of the results presented here. These methods may be easily applied to a larger, more representative sample. The experimental design would remain unchanged as would the estimation procedures. What would differ would be the implications of the estimates of utility, preferences, and value drawn from the results. These results represent the preferences of a small, relatively homogeneous group of resource professionals. Policy decisionmaking requires a much larger (population level) consensus of opinion and as such would find a greater degree of usefulness in these results if they represented a larger segment of the population.

The result of the analysis of the sample of 54 resource professionals from the Vancouver area suggest that the best model of individual utility is the quadratic model. However, the linear model bears some consideration, if only for its simplicity and ease of estimation. While its performance vis à vis the quadratic model was poorer it was not so much so that the model could not serve as a useful alternative model or as a tool for confirming results of other model forms. The greater flexibility inherent in the quadratic functional form is extremely appealing, yet it is noteworthy that many of the quadratic utilities exhibited a linear structure. Finally the quadratic model appears to provide better estimates of the welfare effects associated with an increase in the levels of the six attributes. Although the welfare sum was higher than in the linear case it was not unreasonably so and may in fact be more appropriate for the multi-attribute improvements assessed in the welfare calculations (four attributes were increased in the welfare calculation).

On an individual attribute basis, the models estimated showed an economically rational response to taxation in the form of a negative coefficient to the tax attribute. The utility functions traced out by the different models varied little between the linear and quadratic models for the caribou and pine marten attributes, suggesting that the linear form was appropriate. For the backcountry and heli-skiing attributes, however, the quadratic model differed noticeably from the linear case, suggesting that the utilities of these attributes may peak or plateau over the range examined in this study (and further suggesting that the linear model may be inadequate).

This analysis of consumer choice over forest resource alternatives demonstrates the flexibility of an attribute based approach to valuation and further illustrates a means by which market and nonmarket resource values may be included among the attributes to be valued. Preference based approaches allow comparisons between seemingly incompatible features to take place. Use of stated preference techniques make this possible because of their capacity to model any combination of alternatives and attributes, even those unlikely to occur in the real world. Linking these methods to the diverse and similarly flexible information available from geographic information systems exploits a natural complementarity and enhances the quality of the information gathered.

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ANALYZING MULTIPLE OBJECTIVE DECISIONS ON PUBLIC LANDS

Donald F. Dennis[1]

ABSTRACT.—Public land managers and policy makers need a means to solicit and analyze public preferences and values. A conjoint ranking survey was used to solicit preferences for various levels of timber harvesting, wildlife habitats, hiking trails, snowmobile use, and off-road-vehicle access on the Green Mountain National Forest. The survey was completed by 76 respondents during public involvement meetings. Linear and quadratic main effect components were estimated using an ordered probit model. Respondents preferred moderate levels of timber harvesting and snowmobile access, and lower levels of off-road-vehicle access. They favored a mixture of mature closed canopy and younger, more open forests over either extreme, and were somewhat indifferent toward extending the network of hiking trails.

INTRODUCTION

Those who manage public lands or design policy that affects natural resources must make difficult choices that frequently involve conflicting uses. The public has articulated clearly that their values and preferences must be considered, and that biophysical information and technical expertise alone are an insufficient basis for decisions about resource allocation. Because desires vary widely among individuals and groups, conflict and expensive litigation frequently arise over the choice of management strategies and resulting mix of benefits to be provided on public lands.

Caught between the vocal and unyielding demands of stakeholders, managers seek a systematic and rational means to evaluate alternatives. Externalities, particularly those surrounding common property, often make market-based decisions on allocation inefficient and even inappropriate. Nonpriced costs and benefits are important and must be considered. Differences in units of measure and the nonmarket nature of many natural resource management objectives pose severe problems for traditional modes of analysis.

This research explores the use of conjoint techniques to solicit and analyze public preferences associated with multiple objective decisions involving extramarket values. The empirical portion of this study addresses the solicitation and assessment of public preferences for various levels of timber harvesting, wildlife habitats, and recreational opportunities on the Green Mountain National Forest (GMNF) in Vermont.

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METHODS

Conjoint techniques are used by marketing researchers to measure consumer preferences (Green *et al.* 1988). The objective is to decompose a set of factorially designed stimuli or attributes so that the utility of each attribute can be inferred from the respondent's overall evaluations. In conjoint studies, respondents choose between alternate products or scenarios that display varying levels of selected attributes. These comparative evaluations, which outline a respondent's preferences or the tradeoffs he or she is willing to make, can be used to solve the partial utilities for each attribute that are imputed from the overall tradeoffs. These partial utilities can be combined to estimate relative preference for any combination of attribute levels. Thus, the analyst obtains high leverage between the options actually evaluated by respondents and those that can be evaluated after the analyses.

Conjoint techniques are well suited for soliciting and analyzing the preferences of stakeholders in environmental decisions that frequently involve tradeoffs between costs and benefits that are not efficiently represented in market transactions. Asking respondents to make choices between alternatives mimics the real choices that managers must make, and can provide feedback to stakeholders with respect to the consequences of their choices. For example, Opaluch *et al.* (1993) described an approach that used paired comparisons to rank potential noxious facility sites in terms of social impacts.

Conjoint experiments can be designed and analyzed in many ways. Respondents may be asked to reveal their preferences by choosing one of two or more options, ranking several options, or assigning numerical ratings to

each option. Numerical ratings provide the most information but may place the greatest cognitive demands on respondents. Green (1974), Green and Srinivasan (1978), Louviere and Woodworth (1983), and Louviere (1988) provide information on experimental design within the context of conjoint analysis.

THE GREEN MOUNTAIN NATIONAL FOREST

The 360,000-acre GMNF accounts for approximately 5 percent of the total land area and half of all public forest land in Vermont (USDA Forest Service 1992). Because of its remoteness and relatively large size, the GMNF provides unique opportunities for backcountry recreation and wildlife habitats in a region characterized by nonindustrial private forests and high population density. Public desires for forest related benefits are intense and cannot always be met simultaneously, so a means of assessing preferences and values must be incorporated into the planning process.

National forest planning occurs on three broad levels: national, regional, and forest. The Forest Plan for the GMNF (USDA Forest Service 1992) sets goals, objectives, standards, and guidelines that fit within broader direction specified at the national and regional levels. Forest goals are accomplished through management actions on Ranger Districts and subunits of these districts. Although public input and assessment of human values are important throughout the planning process, this study addresses public preferences for actions below the district level. Techniques and experience developed during this study will be useful in developing broader goals for the next Forest Plan.

The 18,600-acre study area located on the Manchester Ranger District includes two adjacent units known as Greendale and Utley. The area contains a developed campground (14 sites) and land classified in the Forest Plan as Management Area's (MA's) 2.1, 3.1, 4.1, 6.2, and 8.1. The first three listed MA's include opportunities for roaded natural recreation and emphasize uneven-age silviculture (2.1), even-age silviculture (3.1), and winter habitat for deer (4.1). MA 6.2 emphasizes opportunities for semiprimitive recreation while producing high-quality sawtimber by growing trees to an old age. MA 8.1 is the White Rocks National Recreation Area where the emphasis is on protecting wild values. Timber harvesting and roaded recreation are permitted but restricted. Broad management prescriptions, standards, and guidelines are contained in the Forest Plan. Specific management actions are needed for the Greendale and Utley units. The goal is to develop a procedure for assessing and analyzing public preferences and acceptable tradeoffs for various levels of timber harvesting, wildlife habitats, and three recreational opportunities: hiking trails, snowmobile use, and off-road-vehicle (ORV) access.

Timber harvesting on the GMNF is controversial. Some publics argue against the environmental disturbance that accompanies the harvesting of wood products. Proponents argue that harvesting timber generates revenue for local and regional economies by creating jobs and cash payments for wood products exported from the area. It also is used to meet objectives related to wildlife habitat, silviculture, and recreation.

The Greendale/Utley area supports a high species richness with a diverse late successional community of northern hardwoods, hemlock, and spruce. There are opportunities to enhance habitats for a variety of wildlife species through harvesting practices and the creation and maintenance of permanent openings, but it is not clear which species the public would like to see favored. If species associated with early succession habitats are favored, management can be tailored to satisfy this preference. Similarly, management can be structured to favor species associated with mature, contiguous habitats.

Recreational concerns center around opportunities for and potential conflicts between motorized and nonmotorized trail uses. There are opportunities to feature cultural resources (e.g., old roads, bridges, and farm sites) and to view wildlife (sightings of bear, moose, beaver, and birds are common). There are several opportunities to expand the system of hiking trails. Currently, 16 miles of travelway are available for snowmobile use, and there is public interest in expanding the available travelway. However, some users are concerned that increased snowmobile access will disrupt other recreational activities and disturb wildlife. At present, ORVs are not permitted on travelways but there is public interest in obtaining ORV access to the area, and several potential opportunities have been identified. Those in opposition cite ecological damage and disturbances to wildlife or other recreationists as reasons to deny ORV access.

ANALYTICAL MODEL

When presented with a set of alternatives, individuals are assumed to make choices that maximize their utility or satisfaction. The utility that the ith individual derives from the choice of the jth alternative (U_{ij}) can be represented as:

$$(1)\quad U_{ij} = \_\_{ij} + e_{ij} = X'_{ij}b^* + e_{ij}$$

where X_{ij} is a vector of variables representing values for each of M factors or attributes of the jth alternative to the

ith individual, b* is a vector of unknown parameters, and e_{ij} is a random disturbance, which may reflect unobserved attributes of the alternatives, random choice behavior, or measurement error. In the empirical study under consideration, a respondent's utility level (U_{ij}) for each of the J alternatives is not observed but an ordinal ranking (Y_{ij}) is observed that corresponds to the order of his or her underlying utilities. The probability of alternative 1 being ranked above other alternatives is:

(2) $P_{i1} = Pr(U_{i1} > U_{i2}$ and $U_{i1} > U_{i3}$ ... and $U_{i1} > U_{iJ})$
$= Pr(e_{i2} - e_{i1} < \_{i1} - \_{i2}$ ... and $e_{iJ} - e_{i1} < \_{i1} - \_{iJ})$

Similar expressions hold for each of the remaining alternatives being chosen next in the choice set, and the P_{ij}'s become well-defined probabilities once a joint density function is chosen for the e_{ij} (Judge *et al.* 1985).

McKelvey and Zavoina (1975) developed a polychotomous probit model to analyze ordinal level dependent variables. They assume that the e_{ij}'s are distributed normally and that the observed variable (Y_{ij}, the ranks for the J alternatives) is related to the true unobserved utilities (U_{ij}) in the following way:

(3) $Y_{ij} = 0$ if $U_{ij} \leq m_{i1}$, $Y_{ij} = 1$ if $m_{i1} < U_{ij} \leq m_{i2}$, ... $Y_{ij} = J-1$ if $U_{ij} > m_{iJ-1}$

The m_{ik}'s define the boundaries of the intervals for the unobserved utilities that correspond to the observed ordinal response. Since the m's are free parameters, there is no significance to the unit distance between the set of observed values of Y; they merely provide the ranking.

Estimates are obtained by maximum likelihood and the probabilities entering the log-likelihood function are the probabilities that the observed ranks (Y_{ij}'s) fall within the J ranges defined by J+1 m's. The parameters to be estimated are J-2 m's plus the b vector; m_0 and m_J are assumed to be negative and positive infinity, respectively, and m_1 is normalized to 0.

The estimated parameters may be used to calculate the probability that a particular alternative will fall within each response category or rank in the case under consideration:

(4) $Pr(Y_j = k-1) = Pr(U_j$ is in the kth range$) = F(m_k - X'_j b) - F(m_{k-1} - X'_j b)$

where k indexes the rankings and $F(\cdot)$ is the cumulative distribution function, assumed normal for the probit specification. Thus, the effect of a discrete change in the level of the nth independent variable (x_{nj}) on the estimated probability that a response will fall within each of the categories (ranks) can be calculated by substituting the estimated parameters (b and m's) into equation 4. The magnitude of that change will depend on the values for all the estimated parameters and associated variables, as indicated by equation 4.

SURVEY DESIGN

A conjoint ranking survey was designed to solicit preferences for five forest-related attributes: timber, wildlife habitat, hiking trails, snowmobile use, and ORV access. Three levels covering the range of reasonable alternatives for the Greendale and Utley units were selected for each attribute (table 1). Eighteen alternatives, each depicting a unique bundle of attribute levels, were chosen using an orthogonal design that allows estimation of all linear and quadratic main effect components as well as the interactive effect of the timber and wildlife attributes over the entire range of possible attribute combinations, with the least number of trials.

Although in some cases the attribute levels coincide with on-the-ground alternatives, they also are indicators for broad forest related values. For example, changes in miles of travelway available for snowmobile use also may represent perceived changes in the overall snowmobile experience, congestion in parking areas, noise levels, chances for sighting wildlife, tourism revenues for the region, use conflict on trails, and other values perceived by respondents. Similarly, differences in the number and size of openings in the landscape referenced within the wildlife attribute carry aesthetic meaning as well.

Respondents were given an explanation describing concerns and alternatives for the Greendale/Utley area as well as an overview of the nature and purpose of the conjoint study. A brief verbal explanation of the attributes and levels (table 1) was provided and respondents were given the opportunity to ask questions or discuss their concerns. Additional information, such as expected volume of timber harvests for each level of the timber attribute and lists of species favored for each level of the wildlife attribute, was provided. Large overlay maps were used to illustrate locations of forest types, prospective harvests, travelways, and other pertinent information. Respondents then ranked 18 sample cards, each representing a unique alternative depicted by a bundle of forest-related attribute or factor levels for the Greendale/Utley area. Respondents also completed a series of attitudinal and demographic questions.

The survey was administered by USDA Forest Service personnel during public meetings. Those who were unable to attend one of the scheduled meetings were given the opportunity to complete the survey at the local District office. Although efforts were made to attain a broad group of respondents, we did not attempt to achieve representation from every interested group or to

Table 1.—*Choice attributes and levels*

Timber
1. Do not harvest timber
2. Harvest timber on 5-10 percent of the planning area
3. Harvest timber on 15-20 percent of the planning area
Wildlife
4. Favor wildlife preferring contiguous unbroken forests
5. Favor wildlife preferring a mix of young forests and contiguous unbroken forests
6. Favor wildlife preferring open lands and young forests
Hiking Trails
1. Maintain existing hiking opportunities
2. Extend the hiking trail system to include 2 additional miles
3. Extend the hiking trail system to include 6 additional miles
Winter Motorized
1. Do not permit snowmobile use
2. Maintain the existing 16 miles of travelway for snowmobile use
3. Extend the travelway available for snowmobile use to 23 miles
Summer Motorized (e.g., 3- and 4-wheel ORVs, motorized trail bikes)
1. Do not permit ORVs on travelways
2. Provide approximately 5 miles of travelway for ORV use
3. Provide approximately 8 miles of travelway for ORV use

select a random sample of respondents to represent the general public. The goal for this portion of the GMNF's outreach effort was to solicit and analyze the preferences of people who were interested in and willing to participate in the management decisions for the Greendale/Utley area. The results discussed in the next section apply to the population of interested and concerned citizens that is characterized by this sample of respondents.

An ordered probit model was used to analyze data obtained from 76 respondents. Each respondent ranked 18 alternatives providing 1,368 observed preferences. The dependent variable is the ordinal ranking of the alternatives, which was coded from 0 to 17; higher scores were associated with greater utility. The attribute levels (1, 2, 3 in table 1) for the independent variables were coded, respectively, -1, 0, 1 for the linear form and 1, -2, 1 for the quadratic form. This coding scheme maintains the ordinal relationship for the linear term and provides for an orthogonal contrast with the quadratic term and constant.

RESPONDENT PREFERENCES

In general, respondents were fairly affluent. The average level of education was 16 years, indicating completion of college, and the average total family income was within the range of $50,000 to $75,000 per year. Sixty-two percent of the respondents were men and the average age was 48 for all respondents. Nearly all of the respondents were Vermont residents; on average they lived in the state for 23 years.

General inferences about respondent preferences concerning each attribute can be made from the summary of results in table 2. Results and analyses are presented in significantly greater detail in Dennis[2]. The coefficients relate to the orthogonal contrasts and coding of the dependent variable outlined in the previous section. The nature of the overall relationship depends on the signs and relative magnitudes of the estimated coefficients for both the linear and quadratic contrasts. Inferences will be discussed, first with respect to individual attributes and then overall preference for the bundles of attribute levels that comprise alternatives.

[2] *Dennis, D.F. Analyzing public inputs to multiple objective decisions on national forests using conjoint analysis. Unpublished manuscript presently submitted to Forest Science.*

Table 2.—*Ordered probit results (N=1368)*

Variable	Linear effect	Quadratic effect
Constant	+***	
Timber	+***	-***
Wildlife	+	-**
Hiking trails	+*	-
Snowmobile	-	-***
ORV access	-***	-

*** Significant at 1 percent level.
** Significant at 5 percent level.
* Significant at 10 percent level.

The significance of both the linear and quadratic terms for the timber attribute indicates that respondents supported timber harvesting but were indifferent to increases beyond level 2. Complimenting their support for moderate timber harvesting, respondents preferred a mixture of young open and contiguous unbroken forest over either extreme. Although nearly all of the respondents hiked, they generally weighted other attributes more heavily in their rankings and seemed more concerned about alternate trail uses. Although few of those surveyed used snowmobiles, they recognized this activity as a valid use of the area. However, respondents were not tolerant of opening the area to ORVs and registered this sentiment clearly in their rankings.

The optimal mix of attribute levels estimated by the model was: the mid-level for timber harvesting, a mix of open and contiguous unbroken forest, extending hiking trails, maintaining the existing snowmobile network, and not permitting ORV use in the area. The preferred mix was least sensitive to changes in the level of maintained hiking trails. Changes in overall preference resulting from adjustments to any of the other attribute levels as well as the marginal rates of substitution or acceptable tradeoffs among attributes can be readily assessed using the results and analytical techniques discussed here and in greater detail in Dennis[2].

Generally, respondents supported multiple objective management for this area. These results differ significantly from the relatively extreme demands that often are articulated by special interest groups and some individuals. Calls to ban timber harvesting or snowmobiling from an area set the stage for opposite demands from those that benefit from these activities. Managers often are trapped in a lose-lose situation—they are caught between the vocal and seemingly unyielding demands of opposing stakeholders. Conjoint surveys and the ensuing analyses offer a means to sift through the relative values placed on various benefits as well as assess preferences for entire bundles of attributes.

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INCORPORATING BIOPHYSICAL AND MULTIPLE OBJECTIVES IN PLANNING MODELS OF LOW RESOURCE FARMERS IN GHANA: A MULTILEVEL SYSTEMS APPROACH

K. Nkowani, R.H. Fawcett, J.B. Dent, and J. Quashie-Sam[1]

ABSTRACT.—Integrating sustainable land use in a fashion which is sensitive to the wishes of immediate stakeholders and broader society yet avoids biophysical and environmental risks, involves many inherent conflicts. These conflicts can be captured and explored in mathematical programming models (MPM). The appropriate levels of detail can be obtained by imbedding the output from simulation models of biophysical processes into a farm-level socio-economic framework represented in the MPM. Simulated results for different spatial units can be visually represented with the use of Geographic Information Systems (GIS). This approach allows the user to define and simulate alternative farm plans, and to test hypotheses about which are most sustainable and stable.

INTRODUCTION

The development and use of biophysical models to generate key data for farm and regional-level models is now widely acknowledged (Dent and Thornton 1988, Dent and McGregor 1993, Fawcett and Nkowani 1996, Fresco 1995, Jansen 1995). These process based models are useful for pre-screening potential land-use options prior to expensive experimental research, development, and extension programs being committed. Specific attributes would include the identification of suitable germplasm, and the identification of appropriate management packages for a particular locality in response to alternative input strategies. Climate, soil data, and genetic parameters can be varied and results assessed in terms of their suitability. Estimates of yield variability under different crop/tree layouts and mixtures can be assessed in relation to alternative treatments. In addition, modeling speeds the long-term process of testing crops, particularly where it involves the inclusion of trees in the field for suitability and compatibility. The human intervention in the form of husbandry practices specifies the 'treatment' setting the parameters for the simulation run which can span many years. The results of the treatment are 'returned' as matrix coefficients rewarding the husbandry practice.

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The imbedding of the output from simulation models of biophysical processes into the farm-level socio-economic framework provides useful mechanisms to explore ways in which farm households would react to new circumstances (such as a new policy instrument) or would permit a comparison of policy scenarios in terms of economic and social benefits and costs (Dent 1991). This gives an opportunity for decision makers to judge the relative merits of a range of alternative management regimes under various policy scenarios.

Geographic Information Systems (GIS) is a computer-based information system designed to facilitate integration and analysis of geographically referenced data (Mallawaarachchi *et al.* 1996). Generally, it possesses the capacity to store, evaluate, combine, and conditionally extract information from maps and associated attribute data. Simulated results of biophysical process for different climate and soil domains can be used to predict balanced land-use strategies over spatial units, both in the study area and beyond.

However, it remains an elusive goal to integrate socio-economic and productive uses of land while avoiding biophysical and environmental risks as well as being sensitive to the wishes of immediate stakeholders and broader society (Nkowani *et al.* 1995a). Nevertheless, the ability of these models to provide an insight and understanding of the interactions between competing objectives and linkages between all levels, particularly trade offs between economic, social, and environmental imperatives (Cocklin *et al.* 1988), make them appropriate tools to explore constrained resource use options.

The purpose of this paper is to explore the possibilities of setting-up a multitiered modeling framework. Three model levels are suggested: biophysical simulation models (examples of which are provided by Hypar, DSSAT, etc.) which provide crop/tree yields under alternative management to whole farm socio-economic models which define the results of decisions taken by farmers in their daily lives. A similar approach was used by Veloso *et al.* (1994) in a Brazilian context. Aggregate results of individual farmers may be represented in a regional-level model which provides the mechanism for examining the trade-offs between policies for economic development and for environmental enhancement. This paper continues with a brief contextual definition of the problem in Ghana, a short argument about the need for a multilevel systems framework, and a description of how output from biophysical models in conjunction with GIS may be used within a mathematical programming framework, potentially improving the operational efficiency of the farming systems research. It appears that the integration of biophysical modeling output into the socio-economic framework of the whole farming system is both desirable and feasible, although problems remain to be overcome before it can be considered as a routine methodology for the design of appropriate policy and/or technology packages for small holder farmers.

DEFINITION OF THE PROBLEM

Human endeavors to enhance the quality of life of people rest closely with the consumption of natural resources required to generate material wealth and amenities (Mallawaarachchi *et al.* 1996). Land degradation, or more specifically, stock depletion and declines in productivity, have led to wide concerns about the potential endurance of current agricultural production systems (Asamoa 1991). The result has been a call for policies that promote ecologically sustainable development. The challenge to decision makers has been how to raise small holder productivity at farm-level without long-term resource depletion while at the same time recognizing the endemic poverty, seasonal food shortages and disease, poor soil fertility, and seasonal labor shortages already present (Fawcett and Nkowani 1996). Biological methods of maintaining soil fertility, and agroforestry technologies in particular, were suggested as possible means to sustain soil fertility and loss. The aims and rationales of agroforestry systems were to emphasize the positive interaction in order to obtain a higher total, a more diversified and/or more sustainable production from available resources than is possible with other forms of land-use under prevailing ecological, technological, and socio-economic conditions (Nair 1990).

But the non-adoption on a wide scale of alley farming (the most prominent agroforestry system) by Ghanaian and generally West African farmers has been a set back to policy makers, research, and extension workers. The reasons for non-adoption have been documented by Bayliss-Smith *et al.* (1993) and Reynolds (1994). Both studies seem to suggest that the incorporation of farm family objectives into farming systems research should provide a mechanism for rejecting options at the systems design stage where conflicts with family seasonal labor supply, lifestyle, gender issues, tastes, and preferences are significant. A thorough understanding of traditional farming systems is, therefore, a prerequisite both to examining the appropriateness of each option, and in understanding farmers' responses to technology. This paper suggests a multi-tiered modeling framework where broad constraints for the region (e.g., land suitability, climate, soil, credit availability, etc.) are set by the biophysical and socio-economic factors.

THE NEED FOR A MULTILEVEL SYSTEMS APPROACH

It might be assumed that the most appropriate approach to integrating objectives between the land-users (farmers) and those concerned with regional or national development is to create a unified programming model. Such a model is specified by McCarl (1992) to maximize the satisfaction of a regional developer but subject to a *notional* response of the farmer to regional policies. McCarl (1992) argues that such a model is an appropriate conceptualization of the policy process but that it is difficult to solve due to the existence of many local optima. In addition, this author calls for care in the application of such a unified model approach because results can be misleading. Moxey *et al.* (1995) argued that although such an approach may overstate flexibility and coordination of agricultural production, it is a widely accepted means of modeling large areas: a statement backed by Norton and Schiefer (1980).

The development of a region is, however, determined by decisions at micro (family), (village), and regional-levels (Werner 1994). Decisions are made according to the needs and objectives of the decision makers, availability of resources, and constraints. Micro, and regional-levels should be integrated in a multisystems concept to understand and model decisions and linkages at and between levels. The unified (partial) approach can be corrected by using a multistage model which separates the modeling applications between farmers and regional (national) planners as demonstrated in the work by Dent and McGregor (1993). The conceptual development of the multilevel systems approach is illustrated in figure 1.

The three linked parts (see fig. 1) can be interpreted as follows:

(a) Part A is a generalized goal format for a single farm. The model would run for each defined representative

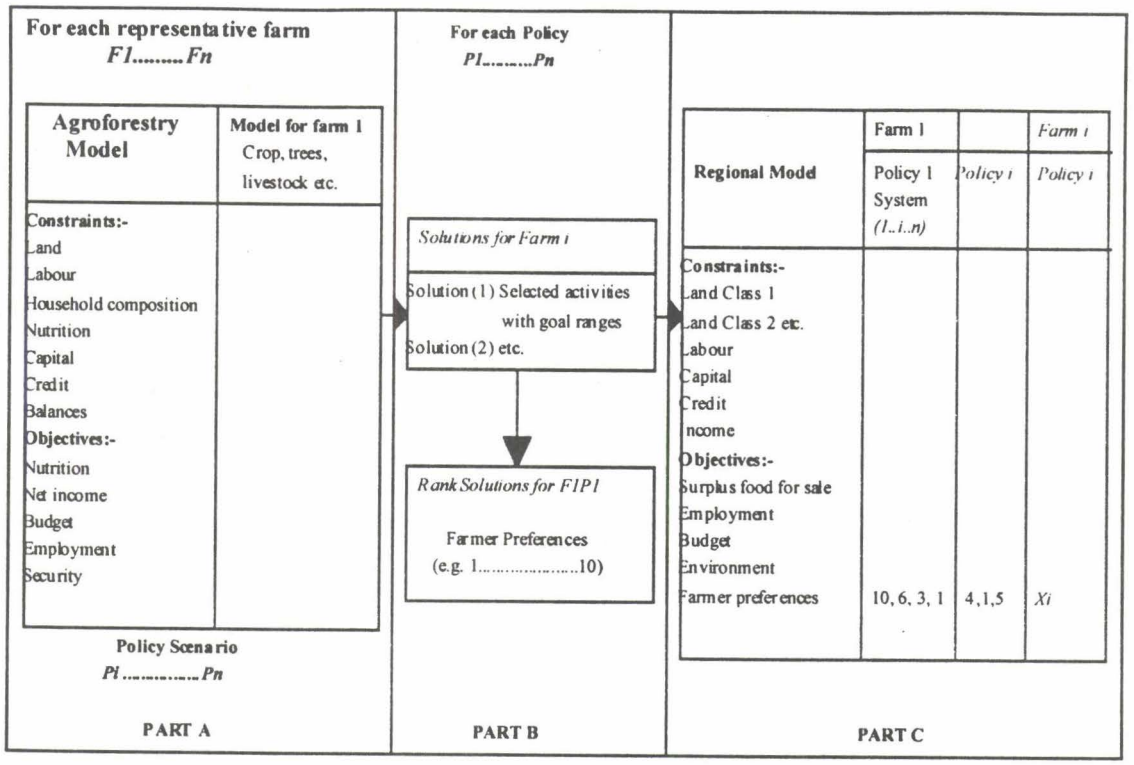


Figure 1.—*The Conceptual Development Framework of a Multilevel Model.*

farm for each spatial unit within the region (F_1 to F_n) with provision for the objectives, goal levels, priorities, and weights to be included.

(b) For each representative farm, the above procedure would be repeated for each potential regional policy (P_1 to P_n). Part B of figure 1 first shows that a set of solutions for F_i and P_i will be generated.

The goal programming model solutions for F_iP_i will provide a set of solutions with different characteristics but all meet the goal ranges and are feasible within the constraints specified. These may be ranked by farmers to reflect their preferences using, for instance, a simple scale (say 1 to 10).

Solution sets for all (F_n) farm household types each operating under all potential (foreseeable) policies (P_n) may now be transferred to Part C of figure 1 along with the relevant farmer preferences. Some culling of solutions may take place at this stage but it would be desirable to retain all options until it is obvious which solutions are dominant.

(c) Part C provides the format of the regional-level model. Constraints may refer, for example, to total regional area available of different land classes and budget. The regional objectives may relate to surplus food for sale and overall or district employment levels. The activities represent each of the solutions for F_i P_i (generated in Part B). Hence, for farm household type 1 and policy 1 there will be a range of possible systems (S_1 to S_n) as shown in Part C. This would be repeated for each policy over all farm household types. The Land Class 1 coefficient for activity S_i will be for the total area in the region required for this type of farm operated under Policy P_i.

An additional objective is defined in the example—farmer preferences. This will indicate the subjective level of preferences which farmers of this type have for this policy and system. The target level can be varied to reflect the speed of uptake or level of acceptance (high target values indicating greater and faster acceptance).

An important feature of the representation is that policy options must be made mutually exclusive but this constraint could be partially relaxed if it was appropriate for different spatial areas to have individual policy specifications.

The successful adoption of this approach, which is conceptually tidy and appealing, is dependent on elicitation of appropriate preference functions from farmers for each policy/system combination once the individual farm models have been developed and run. This framework sets out the farm family objectives and

the resource constraints under which small holders operate, thereby allowing the user to define alternative farm plans, simulate them, and test the hypotheses about which are most sustainable and stable. Sensitivity analyses can also be carried out to examine the effects of different internal and external factors on farm behavior.

INTEGRATION OF BIOPHYSICAL AND SOCIO-ECONOMIC MODELS

Biophysical crop and agroforestry models have developed to a stage where they can provide insight into land-use planning choices for localized small holder traditional and agroforestry systems (fig. 2, Section A). For example, the model (Hypar/DSSAT) used in this study permits the yield of certain tropical and sub-tropical crops such as: maize, cassava, and yam to be predicted in different mixtures and lay-outs with key tree species (e.g., *Leucaena leucocephala, Gliricidia sepium*, and *Cassia siamea*) across a wide range of climate and soil types (Lawson *et al.* 1995). Daily weather patterns are simulated for 1/2 degree latitude/longitude cells using a well-established weather-generator (Richardson and Wright 1984). Predictions of crop yields and yield variation can thus be made on a regional scale over a long-term period (Mobbs and Cannell 1995). Parameterization for a wider range of crops and agroforestry trees is underway, and efforts are being made to extend the database of climate and soil data provided to the model. However, these models remain weak by themselves in their ability to fully appreciate spatial and temporal heterogeneity in agricultural and natural resource systems due to non-incorporation of socio-economic aspects of a farmer.

The storage of the simulated output from biophysical models within a GIS has advantages for this multi-tiered modeling approach. First, the use of a common geo-referencing system enables disparate data sets, previously in the domain of individual disciplines, to be integrated. The implications of the results of biophysical simulations for land-use can then be assessed, based on a more interdisciplinary perspective. Second, the ability to visualize spatial data provides a means for a user to investigate different scenarios, as well as an interpretative tool for the modeler. In this way, the user can define alternative farm plans, simulate them, and test the hypotheses about which are most sustainable and stable. Sensitivity analysis can be also carried out to examine the effects of different internal and external factors on farm behavior.

In Section B of figure 2, data sets from socio-economic questionnaires covering all spatial units (agro-ecological zones) are shown as being formatted on a series of spread sheets to be processed into appropriate statistical entities. This information, when merged with secondary data, is used to establish the socio-economic characteristics of farm and families. Farm typologies are then formulated from the structural and functional description of farms to construct representative farm models for each defined agro-ecological zone. The models developed are used to estimate the optimum value for the objective function for a linear programming farm-level model and serve two main purposes as demonstrated by Nkowani (1996);

(a) to examine options for development or change on typical representative farms.

(b) the output runs, in multiple runs, set-up input data for formulation of a region model.

The linear programming model provides data to focus discussion at the interface between farmers (land-users) and wider community (see fig. 2, Sections B and C). This is a useful device to create dialogue about:

(i) the relationship of the farm systems with the outside community in order to attempt a balance between technology, infrastructure inputs, and socio-economic elements;

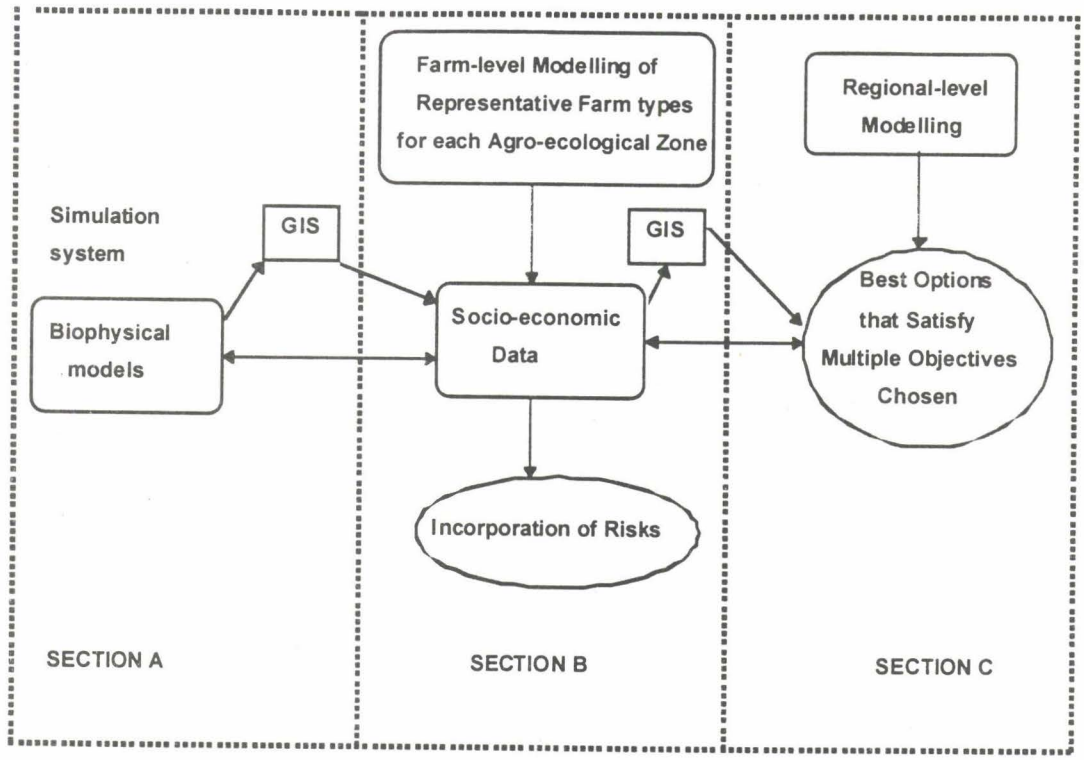
(ii) policy agenda, research, and extension priorities which are set within the wider systems boundary.

The farmers' land-use decision-making process is driven by a number of objectives which include minimizing risks, improving food security, involvement in community, and fulfilling cultural obligations and concerns about income (Nkowani *et al.* 1995b) (fig. 2, Section B). Fundamentally, small holders should be seen in the light of having multiple objectives, and profitability is not the only criterion to decide about a particular mix of crop enterprises.

The information on farmers' objectives on the other hand provide the basis for converting the linear programming models at farm-level into Goal Programming regional model dealing with multiple objectives and the system is operated in pursuit of the goals and aspirations of the decision makers.

A multiple objective linear goal programming model is developed to represent opportunities for change at a regional-level. The model is used to analyze a range of solution sets for all (F*n*) farm household types, each operating under all potential (foreseeable) policies (P*n*) along with relevant farmer preferences with the aim of selecting management options which satisfy the set of regional objectives (see fig. 2, Section C).

The matrix has minimal additional data requirements in that it summarizes the transactions of the real system and



Adapted from Fawcett & Nkowani (1996).

Figure 2.—*Integration of biophysical and socioeconomic models.*

contrasts with the information produced in the biophysical simulation of growth processes which function on a daily basis.

In this approach, a range of land-use management scenarios can be analyzed and management options which meet social objectives, enhances food production and/or food security, and at the same time maintains ecological stability through improved land-use—especially, but not only by the incorporation of trees, into the farming systems can be selected and promoted (see fig. 2, Section C).

METHODOLOGICAL CHALLENGES FOR THE APPLICATION OF MULTILEVEL SYSTEMS ANALYSIS TOOLS

The adaptation of systems analysis tools poses unique methodological issues due to extreme variability of the natural environment. Variation in terrain, soils, pest, disease, and weed levels, in biophysical models, intercropping competition and general land-use produce micro-environments that may be difficult to reproduce in crop, tree, and livestock simulation models. Hence, potential inaccuracies in model assumptions and the uncertainty of environmental variables need to drive the models, and problems related to integrating information at different levels need to be studied. These concerns point to at least four methodological issues.

Aggregation

Understanding of biophysical and socio-economic issues typically occurs at the level of some relatively small unit of analysis, usually the plant or farm household-level. There are still gaps in our understanding of how biophysical, socio-economic, and policy factors interact to affect farming systems. Studies at the components and farming systems level cannot be generalized since the relationships between soils, climate, and vegetation are scale and spatial specific (Fresco 1995, Jansen 1995). This is particularly important when dealing with more than one agro-ecosystem and where heterogeneity of the physical and socio-economic environment is extreme. It is essential that scale appropriate models that can be parameterized for different crop and tree species and for livestock be developed so that, when used in conjunction with GIS and local data, allows the determination of options for land-use for each spatial unit.

Paucity of Data

Detailed data related to current land-use and aspects of management may be limiting. But as Dent (1996) confessed, "models are definable systems developed from understanding basic processes and operationalized by coupling with limited amounts of information". Accordingly, Dent (1991) argues that the development of models that mimic the decision-making processes of

farm-level decision-making unit can help planning for change at regional-level in two ways. The first is that such models provide useful mechanisms to pre-screen the ways in which farm households would react to new circumstances (such as a new policy instrument) or would permit a comparison of a possible policy scenario with another in terms of its economic and social benefits and costs. Second, these models are also useful for pre-screening potential land-use options prior to expensive research, development, and extension programs being committed. This gives an opportunity to decision makers to judge the relative merits of one research development and extension program against another (Edward's-Jones and McGregor 1994, Nkowani 1996). Additionally, for many aspects of production systems and the socio-economic conditions being modeled, there are gaps in understanding or uncertainties regarding the values of particular parameters, so that very detailed representation of the aspects is not warranted (Rae 1994).

The Definition of Socio-Economic Framework

The definition of the socio-economic framework within which the farmers' operate presents problems for modeling studies. As Anderson (1985) notes, it will usually be expedient to side-step the issue of what the society as a whole, and not just the farming sector, regards as being desirable and concentrate on goals and objectives of farm families, while recognizing that there will be times when the goals of other sections of the society simply cannot be ignored. Even if the framework is restricted to the farm family, Dent and Thornton (1988) noted that there are problems in trying to elicit what will inevitably be multi-attribute preference functions. The building of a whole farm model requires that decision-making in constraint-riddled production systems can be represented in some algorithmic way (see Nkowani 1996 for instance). Such assumptions are justified in part by consideration that there is little else that can be done if the problem is to be tackled at all, and that it is better to use an internally-consistent framework than an inadequate one. The practical problems of measurement remains.

Level of Accuracy

Modeling any given system is an elaborate task and requires careful quantification and calibration of many relationships (Nkowani 1996). Choosing an appropriate level of approximation involves making a difficult trade-off between the expense of a larger, more complex model against the benefit of greater precision. The cost of increased size and complexity include not only man hours and computer time but mainly difficulties of understanding the models. Benefits of increased detail are in the dependability of results, although it has been observed that improvements in the accuracy from increased detail are subject to the law of diminishing returns (Morrison *et al.* 1986).

CONCLUSION

It is concluded that the integration of simulation output from biophysical processed models into the socio-economic framework of the whole farming system, is both desirable and feasible, although problems remain to be overcome before it can be considered as routine methodology for the design of appropriate policy and/or technology packages for small holder farmers.

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USING A DECISION SUPPORT SYSTEM TO IMPLEMENT ECOSYSTEM MANAGEMENT ON THE MENOMINEE FOREST: FROM THEORY TO APPLICATION

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ABSTRACT.—A hierarchical planning model was developed based on the needs of managers of the Menominee Tribal Forest in Wisconsin. The model utilizes a non-integer Model I goal programming formulation at the strategic level, and an integer Model II goal programming formulation at the tactical planning level. The strategic model is used first, to set general management direction for 150 years or more. The tactical model is then used to schedule compartment treatments in the first 10-15 years based upon the strategic results. The major use of the model is in planning cover type and age class diversity restoration based on ecological and production considerations.

INTRODUCTION

The forest management approach used by the Menominee tribe of Wisconsin (Landis 1992, Burgess 1996) provides a unique environment within which to explore analytical methodologies to support ecosystem management planning. The Menominee forest is comprised of approximately 205,000 operable acres in over 10,000 stands composed of 13 management cover types on 11 habitat types, as classified by Kotar and Burger (1988).

In our experience, the forest inventory and silvicultural practices used at the Menominee forest are as good as or better than any forestry organization anywhere. The knowledge and data upon which Menominee forest planning is based result from an exceptionally long-term and comprehensive view of their forest from the combined social, ecological, and commercial point of view. Menominee managers recognize the need for long-term planning as a basis for guiding their near-term operations, using a planning horizon of 150 or more years and a "seventh generation" philosophy. This philosophy is interpreted such that all actions taken by current managers must be evaluated in terms of their effects on the seventh generation of their descendants. The Menominee also recognize the link between ecological and economic sustainability, and base a significant aspect of their economic future on the ecological future of their forest.

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This philosophy is the basis of the design of the planning model, TEAMS/M, which we have built to support Menominee forest management planning. The TEAMS/M model was developed based upon requirements specified by Menominee forest managers, after those managers came to the conclusion that existing forest management planning tools were unsuited to their unique requirements. TEAMS/M is in operational use, and has proven useful to Menominee managers in devising strategies for achieving their management objectives. The TEAMS/M model is a direct evolutionary outcome of the principles established and demonstrated in previous versions of TEAMS (Covington *et al.* 1988, Covington and Wood 1991, Wood and Covington 1991).

Briefly, the model is based upon the assumption that the Menominee forest is in key respects a management-driven system, and that the current and future forest results from the management activities humans have and will impose on it. The legacy forest (Covington and Wood 1991) is the forest left to future generations as the result of management actions, and the Menominee look seven generations into the future. In designing a legacy forest, it is useful to ask the question "What forest conditions would we have liked to have inherited from forest managers of the past?", and use that as a reference point in thinking about what we should leave for the future. Because the management objectives of tribal managers may change over time, either in response to changes in the forest or to evolving ecological knowledge or desires of the Menominee people, TEAMS/M has features which allow for great flexibility in redefining management strategies or objectives over time. The Menominee forest was certified as sustainably managed by Scientific Certification Systems and Smart Wood in

1992. These certifications document the fact that the wood products sold by Menominee Tribal Enterprises are produced in a socially and ecologically sustainable fashion, allowing the tribe preferential access to many markets.

MODEL DESIGN

The TEAMS/M model consists of 2 linked goal programming matrix generators, which generate tableaus in standard MPS format which are solved using commercial mathematical programming software. The first matrix generator, which addresses strategic-level (e.g., landscape-level, multiple rotation) planning, builds management formulations using non-integer goal programming and Model II (Johnson and Schuerman 1977) design. The second matrix generator schedules, on a yearly basis, the activities determined for the first planning period by the strategic model to set the path towards achievement of the legacy forest objectives, and uses a mixed-integer goal programming formulation and Model I (ibid.) design. Results from both models are incorporated into the Menominee Tribal Enterprises management information system (MIS) for use in evaluating alternative management options.

Both matrix generators construct management science formulations dynamically from user-defined management strata and a set of management objective and constraint parameters provided from the Menominee MIS. The strategic model is used first, to set long-term management direction for the forest, while the tactical model is subsequently used to allocate the first period management activities to compartments or landscape units. Decisions with respect to snag recruitment or retention, preservation of wildlife trees, and other site-specific ecological management issues are made as a part of operational planning, and is beyond the scope of the TEAMS/M model. It is our view that such tree-by-tree decisions are best made on the ground by well-trained ecosystem management professionals, and that a model can never equal the judgment of a professional looking at the situation on the ground.

The evolution of forest attributes or conditions over time is tracked via accounting variables in the management science formulations. TEAMS/M does not include a conventional biological or ecological simulation model (e.g., there are no regression-based growth estimators), but the model does track the evolution of gross structural characteristics (such as cover type area by habitat type, age class distribution by cover type, and area harvested by period) under alternative management policies over long periods of time.

To maximize the adaptability of TEAMS/M to different management situations, a fundamental element of the design of TEAMS/M is that it is stratum-based, and that the strata are dynamically developed outside of the model. This allows any management problem which can be represented by even- or all-aged management strata based upon cover types and habitat types to be modeled. The definitions of cover types, habitat types, and age classes are set by the user, and can therefore be used to represent a wide range of possible management problems. A self-scaling/self-adjusting software design, object-oriented programming techniques, and an analytical approach which allows for representation of complex management relationships in simplified form were used in the development of the model.

DEFINITION OF INPUT STRATA

TEAMS/M is a stratum-based model. The model is driven by the Menominee management information system, which summarizes stand-level inventory, continuous forest inventory information, geographic information, and a silvicultural prescriptions database into management strata and treatment options for use by the model. For purposes of preparing a data stratum for use in TEAMS/M, all stands within the same landscape unit which are of the same cover type on the same habitat type with the same set of management options, regardless of their current structure, are combined into a single data stratum. The even-aged areas within the stratum are classified according to age, while the all-aged areas of the stratum are assigned to an all-aged category. A maximum of 25 age classes are allowed, and they may be of any length up to 25 years each, but all age classes must be the same length. This gives the model the capability of representing even-aged cover types up to a maximum of (25 * 25 =) 625 years in age.

Four basic management options are possible for each stratum: natural conversion to another cover type (e.g., an overstory removal which allows natural regeneration/ conversion to another species), forced conversion to another cover type (e.g., clearcutting followed by planting), and regeneration of the same cover type using either even-aged or all-aged management. Because habitat types and cover types are defined by the user through a control file, and the user has control over this definition, it is possible to define habitat types and cover types in any way meaningful to the user and to the analysis, thus providing great potential flexibility in the application of the model.

STRUCTURE OF THE STRATEGIC PLANNING MODEL

The Menominee have translated their planning problem into the following management objectives:

- achieve long-term regulation of even-aged cover types to maintain a sustainable balance of age classes with appropriate representation of mature age classes

- using a featured species concept, restore and maintain cover type/habitat type associations, emphasizing high value and high productivity timber species
- convert management of each cover type to a preferred system for that type (even- or all-aged) as designated by managers based on ecological and silvicultural considerations
- achieve a balance of cover types within each habitat type and forest-wide
- provide for a sustained steady flow of timber from the forest from both even-aged and all-aged management activities
- limit the personnel and investment required for planting by period

The management indicators used to set goals to achieve these management objectives are as follows:

- legacy area by cover type for the entire forest
- legacy age class distribution for each even-aged cover type for the entire forest
- legacy area by cover type for each habitat type
- area of forced conversion (planting) by period
- area harvested by cover type and in total by period

The strategic model serves to assist in finding an acceptable management solution to the goals established relative to all of these management indicators simultaneously, using a planning horizon of 150 years or more. In the strategic model, evolution of forest structure is modeled by the area of each cover type on each habitat type which is in each age class, or is in all-aged management. Menominee managers have developed optimal, minimum, and maximum harvest ages for each even-aged cover type based upon historical information, ecological knowledge, and production considerations. Stratum decision variables are automatically generated which reflect the possible treatments and timing options for each stratum, according to the set of management options specified for each stratum, the length of the planning horizon, and the minimum and maximum harvest ages for the cover types specified by managers. If the age of a stratum and the rotation ages of the even-aged cover types are sufficiently short for multiple rotations to be possible within the strategic planning horizon, second and if necessary third entry decision variables are also generated, using a Model II formulation.

The function of the strategic model is to select a mix of treatments which, when applied to age classes of strata at specific times, will satisfy the management goals. The model selects the harvest timing of each management stratum element (e.g., acres of an age class) between the time it reaches minimum and maximum harvest ages, and selects one of the previously identified management options to be applied at that time. The management option selected for each management stratum is limited to the set of options identified by managers. No stratum may be harvested before minimum harvest age, and all strata must be harvested at or before maximum harvest age, but the selection of these ages is left to the discretion of managers and may be easily adjusted as necessary. All-aged strata receive treatments every period.

Based on the timing and treatment selected, the state of the management stratum element with respect to cover types, management regime, and/or age class in the legacy forest is calculated via accounting equations. For example, if each planning period is 10 years, and the planning horizon is 10 periods long (100 years), an area harvested in the first period will be between 90 and 100 years old in the tenth period legacy forest. Constraints restrict the ages at which harvesting occurs, to ensure the total acres harvested of a management stratum in a period does not exceed the total acres of each management stratum (e.g., given possible prior treatments) in that period which are above minimum harvest age. Acres must be treated in the period in which they attain maximum harvest age.

Since the strategic Model II formulation references all activities with respect to outcomes in the legacy forest, the model does not internally track forest structure or species composition in intermediate planning periods, nor does it provide facilities for setting goals with respect to intermediate forest conditions on the path to achieving the legacy forest. Although it is mathematically possible to accomplish this, with a problem of the size and complexity of the Menominee strategic model it would have caused the model to combinatorially expand, potentially to an insoluble size. Instead, reporting facilities outside of the planning model are used to calculate, for each planning period, the forest composition and structure resulting from a given treatment schedule. Since the composition and structure of the forest at the beginning of the management plan are known from inventory information, and the model provides treatment specifications for each treated management stratum by period, intermediate states of the forest may be calculated. By analytically aging the initial inventory and applying the treatments as specified in the model outcomes, the composition and age class structure of the forest in intermediate periods may be calculated for any scenario.

STRUCTURE OF THE TACTICAL PLANNING MODEL

Once an acceptable strategic planning solution is found, the purpose of the tactical planning model is to distribute the activities scheduled for the first planning period across landscape units (compartments in the Menominee

case) by year. The Menominee forest is comprised of 109 management compartments, each with a unique composition with respect to habitat type, cover type, and age class distribution. The tactical model serves to equalize the level of activity and harvest from year to year, to coordinate activities with the compartment entry schedule, and to ensure that the activities required to establish the management path towards the legacy forest are actually accomplished.

The tactical model planning horizon is the same as one strategic planning period: up to 25 years. The tactical model functions via extraction of the first period treatment specifications from the strategic planning results, development of compartment-level timing options to accomplish the specified strata treatments, and selection from among the set of compartment-level timing options via mixed-integer goal programming, using a Model I design. The compartment-level timing options are generated automatically, and define packages of possible compartment entries within the first planning period.

First, the model allocates treatments across the compartments proportional to the amount of each stratum to be treated which is present in each compartment, in the case of treatments to even-aged strata using an "oldest first" rule. This rule causes the model to first work through all compartments, selecting the oldest acres of the target stratum, then working through the compartments again selecting the second oldest, then the third, etc., until the total acres selected are equal to the acres which must be treated according to the specifications from the strategic model. Thus, compartments which have a disproportionate share of the older age classes will have a disproportionate share of the allocated treatments. Age classes which will only be partially treated, as well as the all-aged treatments, are allocated proportionally based on the amount of each stratum of the appropriate structure which is present in each compartment.

Timing options are then generated for each compartment which represent all possible combinations of initial entry years and frequency of entries given the parameters for each compartment specified by Menominee managers. The targeted stratum treatments for even-aged strata are equally distributed between entry years for each timing option, while the treatment of all-aged strata may be either distributed across entries or done in only one of the entries, depending on preferences expressed by managers. The number of entries per compartment within the period can also be set individually for each compartment, allowing particularly large or small compartments to be treated in either a single or multiple entries within the period. The year of last entry into the compartment may be specified as well, preventing the generation of timing options which would violate adjacency/greenup restrictions. Like rules applied to many similar forests (e.g., USDA Forest Service lands), Menominee policy imposes an adjacency/greenup requirement which specifies a minimum of 3 years between treatment of adjacent areas to limit the size and frequency of disturbances and their impacts on soil, vegetation, and wildlife, and to allow for some recovery between entries. Since specific harvest blocks are not mapped in our approach, the compartment-level timing options are automatically developed such that no compartment is entered more frequently than the length of the greenup requirement period, ensuring that harvests in adjacent areas cannot occur at intervals shorter than the greenup requirement.

Each timing option variable represents a "package" of stratum treatments applied in particular years which, taken together, accomplish the treatment targets specified for all of the strata within that compartment for the first planning period. The first period stratum treatments specified by the strategic planning model are automatically installed as the goal targets for the tactical model, becoming the right-hand sides of the corresponding goal equations. The tactical model then selects, via mixed integer goal programming, a treatment package for each compartment. When combined with the timing options assigned to the other compartments, the tactical model seeks to achieve the first period treatment targets while distributing activities and harvests relatively equally between years within the first planning period.

Hierarchical approaches which ignore spatial location at the strategic level may over-estimate harvest levels which may actually be achieved operationally. Underachievement is the result of site-specific operational restrictions (e.g., minimum or maximum treatment block sizes, previous harvesting patterns, adjacency/timing restrictions, etc.) which are not recognized in the strategic model. In the near-term, this is addressed via feedback between the tactical and strategic models. The strategic model allows for treatment prescriptions to be imposed for any planning period (e.g., requiring that a given amount of a specific treatment be applied to a particular cover type on a particular habitat type in a particular compartment in a particular period). Using this facility, the treatments achieved operationally may be installed as constraints in the strategic model. The model is then re-run to assess the effects of the actual treatments on the strategic plan and the legacy forest, and to determine what other compensating adjustments may be necessary.

ADJUSTMENT OF TARGETS AND GOAL/LIMIT PENALTY WEIGHTS

The major difference between goal programming and linear programming is the structure of the objective function (Field 1973). In goal programming, the objective function is structured to minimize the total penalties associated with deviation from the goal levels established

for the management indicators. Two major sets of inputs are required from the user. The first of these is the specification of goal levels for each management indicator. In TEAMS/M, the goals are set by the user based upon an external decision process which defines desirable legacy forest conditions. This follows the same general notion as Field (1973) and Arp and Lavigne (1982), who rely on the analyst and the planning process to determine what the target levels should be based on judgment and intuition. It is possible, of course, that target levels chosen in this fashion may be less than the target levels which could actually be achieved without cost to some other objective, yielding a dominated or interior solution.

The second major input required from the user is the specification of the penalty weights associated with each goal. Penalty weights express the relative importance of individual goals with respect to each other, and to compensate for resources measured in different units or which assume greatly different values. Zeleny (1982) suggests an approach using a cardinal-weighting system where the value of the penalty weights required to achieve a satisfactory solution have no intrinsic meaning. In our model, it is the achievement of satisfactory characteristics in the final solution which is important, rather than the value of the penalty weights required to achieve it. This is the approach which has been followed in TEAMS/M, as we concluded that manual adjustment of penalty weights to achieve a desired legacy forest "mix" and compliance levels with the other goals was acceptable. This approach has been shown in operational use to provide management solutions acceptable to managers.

Many of these goals utilize two sets of underachievement and/or overachievement variables to construct a "stepped" penalty function for deviations from the specified targets, in a fashion similar to that used by Bell (1976). These operate such that an initial level of penalty is assessed for deviations from the target goals up to a certain level of deviation (the over- and/or underachievement penalties), and then a higher level of penalty is assessed for deviations beyond this level (the upper and/or lower limit penalties). This structure serves to allow the user to restrict deviations from the goal targets more tightly if they exceed an acceptable range.

It is of course possible that without sophisticated post-optimality analysis and goal ranging techniques, a dominated or interior solution may be produced and accepted as a management plan. If used in a rigid, one-pass planning process without significant exploration of alternative scenarios or targets, the model could result in a misleadingly narrow view of potential strategies and achievable outcomes. If used as designed, to explore a range of possible legacy forest scenarios in an ongoing iterative process of management design, the risk of adopting a suboptimal strategy is greatly reduced, as the management team gains a comprehensive understanding of the problems and opportunities. This latter approach has been the case in the Menominee use of TEAMS/M.

CONCLUSIONS

We decided upon an approach which will quickly and efficiently generate many "good" solutions, rather than building a model which after lengthy analysis would produce one "perfect" solution. That perfect solution would, in any case, never likely be actually implemented exactly as specified (Daugherty, 1991). The planning environment is constantly changing, as new issues emerge and new knowledge is acquired, and combined with the unpredictable nature of disturbance processes in forests this makes for a very dynamic planning environment. TEAMS/M can provide a new set of strategic and tactical planning solutions for a forest of the size and complexity of the Menominee forest in a few hours, and this can be accomplished by local managers without requiring the support of highly skilled operations research specialists. In our view, having a real-time planning tool which can be used to continuously update management plans at the landscape level, explore new options, and translate these plans into operational guidelines at the landscape unit level far outweighs the risk that any of these individual plans will be suboptimal. A socially acceptable solution need not necessarily be economically optimal, particularly if the solution achieves important social or ecological objectives.

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ISSUES IN THE ESTIMATION OF DYNAMIC MICROECONOMIC MODELS OF FOREST USE

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ABSTRACT. —To date the literature on the microeconomics of forest management has had a normative focus: what forest managers *should* do to maximize a particular objective function. This paper has a positive focus, with particular emphasis on the estimation of dynamic structural models of forest use and their reduced form counterparts.

INTRODUCTION

In the analysis of dynamic decision problems, the vast majority of the literature has focused on the *normative* aspects of such problems: what resource managers *should* do to maximize a particular objective function. So, for instance, the Faustmann model and its many derivatives address the question of when a timber stand *should* be harvested or thinned. There are two reasons for research on the normative questions of dynamic resource management. The first is purely pedagogical: the matter of how to allocate resources over time is a difficult one, and mathematical models of the decision process provide insights to the underlying economics. The second is practical: resource managers and policymakers wish to know how a resource should be managed over time to maximize a particular objective function, such as expected net revenues.

Rarely have resource economists employed their models in the pursuit of the *positive* question; that is, what decision problem do resource managers actually solve? Usually in statistical inference concerning the actual decisions of resource managers and users, dynamic models are treated rather allegorically, with the analyst turning to them for inspiration—to determine, for instance, what variables to use in a linear regression—but never estimating the models directly. The primary explanation for this shortcoming in the literature is that such estimation is computationally very difficult. It usually requires a large amount of computer processing time, and perhaps more importantly, it requires a substantial amount of difficult programming by the analyst. Nonetheless, in the economics literature the estimation of dynamic decision processes has continued to grow rapidly. Most of this literature has concerned dynamic decisions that are dichotomous. Examples related to agricultural and resource economics include the timber harvest decision (Provencher 1995a, b); the decision to take a recreational fishing trip (Provencher and Bishop 1997); and the decision to cull a cow from a dairy herd (Miranda and Schnitkey 1995).

This paper is motivated by the perspective that in the near term the greatest potential for economics to contribute to an understanding of applied dynamic resource management will be positive rather than normative. Over the past 20 years economics has made a substantial contribution to the theory of dynamic resource management; its pedagogical contribution will remain substantial. But its normative contribution to applied dynamic resources management has been and will continue to be minor, for the simple reason that the "curse of dimensionality" prevents the development of decision models that fully reflect the complexity of the social, biological, and physical processes characterizing the decision environment.[2] Without such complexity, resource managers are likely to dismiss the models as irrelevant academic exercises. In dynamic analysis, models with six to eight state variables are computationally very large; yet in my experience resource managers judge such models to be wholly inadequate as decision-making tools.

As discussed below, the curse of dimensionality is even *more* of an issue in the estimation of dynamic decision problems than in the normative solution of such problems, suggesting that if anything, to be computationally tractable a model used in estimation of a dynamic decision problem must be *simpler* than its normative

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[2] *The curse of dimensionality refers to the phenomenon that the computational complexity of a solution algorithm —the number of executable statements necessary to solve a problem— increases exponentially with the dimensionality of the problem. In dynamic programming, references to the curse usually concern the dimension of the state space, though it applies to the dimensionality of the decision space as well.*

counterpart. Yet the very feature of normative dynamic analyses that leaves them unattractive to resource managers is their simplicity. How then to reconcile the need for tractable models to the contention that economics has much to contribute to the positive analysis of dynamic resource management? The answer is forthcoming from almost any good econometric analysis of behavior. Show such an analysis to the "agent" represented by the model—a consumer, producer, or bureaucrat—and the agent would surely argue against the simplicity of the model. Yet economists continue to use these models, supposedly because they do reasonably well in predicting behavior. Indeed, it appears that the literature on the economics of dynamic resource use is unusual if not unique in its normative emphasis. So the justification for using relatively simple dynamic models to explain the behavior of resource users is that such models do a reasonably good job of capturing the underlying decision process; though resource users and managers may claim that a large variety of factors affect their decisions, the analyst develops a representative model in which the decision process is conditioned by a few key variables. A multitude of other factors may influence the agent's decision, but from the perspective of the analyst these other factors are the unobserved elements of a stochastic process.

In the discussion below I illustrate the essential features of structural estimation of dynamic decision problems by examining a simple model of timber harvesting. I then discuss reduced form estimation of the associated decision rule, and briefly examine the relative merits of structural and reduced form estimation.

STRUCTURAL ESTIMATION OF A DYNAMIC DECISION PROBLEM

To keep the presentation manageable, I focus on the matter of estimating an optimal stopping problem, in which the decision-maker merely chooses whether or not to let an activity continue. Let i=0 denote the decision to continue the activity, and let i=1 denote the decision to stop. The amount of the payoff in a period depends on the state variables $\mathbf{x}$, which evolve over time according to the probability density function $f(\mathbf{x}_{t+1} \mid \mathbf{x}_t)$ the decision-specific random shock ε^i, and perhaps other variables, denoted by the vector $\mathbf{y}$, that are invariant over time. The random shocks are contemporaneously observed by the decision-maker but never observed by anyone else; in particular, they are not observed by the analyst. For simplicity we assume these shocks are additive, and identically and independently distributed over time. Letting $R^i(\mathbf{x}_t,\mathbf{y}) + \varepsilon_t^i$ denote the decision-specific payoff at time t, the relevant decision problem can be stated,

(1)

$$V(\mathbf{x}_t,\mathbf{y}) = \max \left\{ R^0(\mathbf{x}_t,\mathbf{y}) + \varepsilon_t^0 + \theta E\left\{V(\mathbf{x}_{t+1},\mathbf{y})\right\},\ R^1(\mathbf{x}_t,\mathbf{y}) + \varepsilon_t^1 \right\}$$

where θ is a discount factor.

The problem in equation (1) reflects Bellman's principal of optimality; in particular, the expected value of not stopping the activity in period t implicitly recognizes that optimal decisions are made in the future. This problem can be solved via the recursive methods of dynamic programming. The solution is an optimal decision rule $i(\mathbf{x}_t,\mathbf{y},\varepsilon_t;\Gamma)$, where ε_t denotes the difference $\varepsilon_t^1 - \varepsilon_t^0$, and Γ is the set of structural parameters associated with the decision problem.

This basic problem can be adapted to the timber harvest decision on even-aged timber stands held in nonindustrial private forests (NIPFs)—those forests held by landowners not directly involved in the manufacture of forest products. The issue of timber harvests on NIPFs has received a considerable amount of attention in the forest economics literature because nationally these forests comprise about 75 percent of commercial timberland, and there is concern among forestry professionals that these forests are not well managed.

Formally, let s_t denote the age of the timber stand at time t, and let $u(s_t)$ denote a money measure of periodic utility from the standing forest. Following the previous literature, the utility received by NIPF owners from the standing forest depends on the age of the timber stand. Also, let p_t and $v(s_t)$ denote the price and volume of timber, and let λ denote the market value of bare forest land–it is the salvage value associated with the decision to harvest the timber stand. It follows that here $\mathbf{x}_t$ is comprised of the state variables p_t and s_t, and

$$\begin{aligned} R^0(\mathbf{x}_t,\mathbf{y}) &= u(s_t) \\ R^1(\mathbf{x}_t,\mathbf{y}) &= u(s_t) + p_t v(s_t) + \lambda \end{aligned}$$

Now suppose there exists observations over time $t=1,\ldots T$, and across individuals (or firms) $j=1,\ldots J$, of decisions i_{jt} and variables $\mathbf{x}_{jt}$ and $\mathbf{y}_j$. The probability of harvest by individual j at time t is defined by equation (2) below

$$\begin{aligned} \Pr(i_{jt}=1) &= \Pr\left(R^1(\mathbf{x}_{jt},\mathbf{y}_j) - \left[R^0(\mathbf{x}_{jt},\mathbf{y}_j) + \theta E\left\{V(\mathbf{x}_{j,t+1},\mathbf{y}_j)\right\}\right] + \varepsilon_{jt} > 0\right) \\ &= \Pr\left(\varepsilon_{jt} > R^0(\mathbf{x}_{jt},\mathbf{y}_j) + \theta E\left\{V(\mathbf{x}_{j,t+1},\mathbf{y}_j)\right\} - R^1(\mathbf{x}_{jt},\mathbf{y}_j)\right) \\ &= \int_{\varepsilon > A} g(\varepsilon \mid \sigma_\varepsilon) \end{aligned} \quad (2)$$

where $A = R^0(\mathbf{x}_{jt},\mathbf{y}_j) + \theta E\left\{V(\mathbf{x}_{j,t+1},\mathbf{y}_j)\right\} - R^1(\mathbf{x}_{jt},\mathbf{y}_j)$

and $g(\varepsilon \mid \sigma_\varepsilon)$ is the probability density function of ε. Let Γ denote the vector of structural parameters, which includes the discount rate, parameters of the payoff

functions $R^i(\cdot)$, parameters of the distribution function $f(\cdot)$, and the distribution parameters σ_ε. Formally, the likelihood function is

$$L(\Gamma) = \prod_{j=1}^{J}\prod_{t=1}^{T} \Pr(i_{jt} \mid \mathbf{x}_{jt}, \mathbf{y}_j; \Gamma) = \prod_{j=1}^{J} L_j(\Gamma) \quad (3)$$

Note that estimation of Γ is a complicated and computationally intensive exercise, much more so than is found with typical static models. The search for the parameter vector that maximizes the likelihood function involves solving the decision problem (1) *each time* new parameter values are evaluated in the search; this is apparent by the presence of $E\{V(\mathbf{x}_{j,t+1}, \mathbf{y}_j)\}$ in the limit of integration in equation (2). Maximum likelihood estimation thus involves the nesting of an "inner" dynamic programming algorithm within an "outer" hill-climbing algorithm (Rust 1994).

THE REDUCED FORM ALTERNATIVE

Given the difficulty of estimating an appropriate structural model, it would appear reasonable to turn instead to estimation of the dynamic decision rule $i(\mathbf{x}_t, \mathbf{y}, \varepsilon_t; \Gamma)$. Probit and logit regression can be rationalized as attempts to do this. One might suppose, for instance, that the decision rule is characterized by a latent variable i^*_{jt}, the value of which is linear in the original variables:

$$i^*_{jt} = \beta_x \mathbf{x}_{jt} + \beta_y \mathbf{y}_j + \varepsilon_{jt}, \quad (4)$$

where β_x and β_y are conformable vectors of parameters. The decision i_{jt} relates to the latent variable i^*_{jt} as follows:

$$i_{jt} = \begin{cases} 1 & \text{if } i^*_{jt} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

and so letting $g(\varepsilon|\sigma_\varepsilon)$ denote the probability distribution function of ε, where σ_ε is a set of parameters defining the distribution, the probability of observing termination of the activity by individual j at time t is given by

$$\Pr(i_{jt}=1) = \Pr(\beta_x \mathbf{x}_{jt} + \beta_y \mathbf{y}_j + \varepsilon_{jt} > 0) = \Pr(\varepsilon_{jt} > -\beta_x \mathbf{x}_{jt} - \beta_y \mathbf{y}_j), = \int_{\varepsilon > A} g(\varepsilon \mid \sigma_\varepsilon) \quad (6)$$

where $A = -\beta_x \mathbf{x}_{jt} - \beta_y \mathbf{y}_j$. Now define $\Gamma r = (\beta_x, \beta_y, \sigma_\varepsilon)$, and let $\Pr(i_{jt}|\mathbf{x}_{jt}, \mathbf{y}_j, \Gamma^r)$ denote the probability of observed decision i_{jt}. Then if the random shock is independently and identically distributed over time and across individuals, the associated likelihood function is simply

$$L(\Gamma^r) = \prod_{j=1}^{J}\prod_{t=1}^{T} \Pr(i_{jt} \mid \mathbf{x}_{jt}, \mathbf{y}_j, \Gamma^r) = \prod_{j=1}^{J} L_j(\Gamma^r) \quad (7)$$

REDUCED FORM VS. STRUCTURAL ESTIMATION

Several observations about reduced form estimation are relevant to evaluating its merit. If the analyst is only interested in identifying the decision rule associated with a particular dynamic decision problem, and in particular, wishes to determine what factors affect the dynamic decisions of resource users and managers, then reduced form estimation is certainly an appropriate tool. Moreover, by casting the estimation as the attempt to recover the underlying decision rule of a dynamic decision problem, the analyst establishes grounds for including higher-order terms in the estimation. Indeed, in the case of the simple optimal stopping problem described above, higher-order terms are necessary to avoid misspecification bias. A comparison of the first lines of equations (2) and (6) reveal that if the structural model is the "true" decision model, then the latent variable in the reduced form model implicitly denotes the expected net gain from stopping the activity, where the expectation is taken over the future value of the activity. It follows that a reduced form model in which the latent variable is linear in the original variables is appropriate *only* if the expected net gain from stopping the activity is itself linear in the original variables. Formally, we require

$$\beta_x \mathbf{x}_{jt} + \beta_y \mathbf{y}_j \equiv -A \equiv R^1(\mathbf{x}_{jt}, \mathbf{y}_j) - [R^0(\mathbf{x}_{jt}, \mathbf{y}_j) + \theta E\{V(\mathbf{x}_{j,t+1}, \mathbf{y}_j)\}], \quad (8)$$

where A is the limit of integration in equations (2) and (6). For our simple model of NIPF owner behavior, equation (8) can be restated

$$\beta_0 + \beta_1 s_{jt} + \beta_2 p_t \equiv -A \equiv p_t v(s_t) + \lambda - \theta E\{V(s_{j,t+1}, p_{t+1})\}, \quad (9)$$

which states that the expected net gain from harvesting is linear in timber price and stand age. Generally this is not true. Consider, for instance, the case where the price expectations of NIPF owners take the naïve form examined by Brazee and Mendelsohn (1988); in particular, NIPF owners suppose that observed prices are

random fluctuations around a fixed mean price. In this case $E\{V(s_{j,t+1}, p_{t+1})\}$ is *not* a function of the current price p_t, and so clearly equation (9) cannot hold so long as the volume function $v(s_t)$ is anything but a constant. Standard probit estimation omits a relevant dependent variable (total revenue, $p_t\, v(s_t)$), and includes an irrelevant dependent variable (p_t). Still another problem is the implicit attempt to represent the discounted expected value function and includes an irrelevant dependent variable (p_t). Still another problem is the implicit attempt to represent the discounted expected value function $\theta E\{V(s_{j,t+1})\}$ as a linear function of s_{jt}. In summary, the structural model is implicitly associated with a decision rule $i(\mathbf{x}_t, \mathbf{y}, \varepsilon_t; \Gamma)$ which, as indicated by the discussion above, one would expect *can* be well-approximated in reduced form estimation.

Still, there would appear to be some merit to stating the structural model representing the underlying decision process, even if the reduced form model is the one eventually estimated, as this could provide some insight to the appropriate estimation procedure, and to the structure of the decision rule (that is, the structure of the reduced form model). Consider, for instance, the case where the analyst draws NIPF harvest data from two regions distinguished by timber prices, such as the coastal plain and piedmont of North Carolina. In reduced form estimation of the harvest decision rule we might expect explanatory (state) variables to include timber price and some measure of the state of the forest stand, such as stand age or volume per acre. In the absence of an explicit linkage between the structural and reduced form models, the analyst is tempted to estimate a *single* reduced form model, combining the data from both regions. But this would be a mistake. The decision problems solved by timber managers in the two regions are different; what the analyst recovers from estimation are coefficients that reflect the "true" reduced form coefficients of neither region. Consider, for instance, simulation results from a timber harvest model similar to that presented by Haight and Holmes (1991). Simulations were run for 150 timber stands from each of two regions distinguished by the stochastic process governing timber prices. In region 1 prices fluctuated randomly around a mean price of \$75/mbf, with a standard deviation of \$6.25/mbf, and in region 2 prices fluctuated randomly around a mean price of \$150/mbf, with a standard deviation of \$12.50/mbf. For such a model, the optimal harvest decision rule is characterized by a reservation price strategy in which a stand of age s is harvested only if the observed price is greater than the reservation price, $p^*(s)$ (Brazee and Mendelsohn 1988). It follows that in each region, price has a positive effect on the decision to harvest. Yet if harvest data are combined in a single probit or logit regression, the positive sign on price will be substantially "diluted," because in region 1 (the low price region), harvests are observed at prices for which the optimal decision in the high price region is to not harvest. Indeed, when each region is treated separately in a regression using observations generated by Monte Carlo simulation of 300 timber stands, the sign on price is positive and significant, as expected. On the other hand, when the regions are combined in a single regression using observations generated via Monte Carlo simulation of 300 timber stands (150 from each region), the sign on price is *negative* and nonsignificant. In repeated trials the coefficient on price in the single regression is in the neighborhood of -0.0007, and the t-statistic is in the neighborhood of -0.8. The upshot is that reduced form estimation requires that the analyst fully differentiate among the dynamic decision problems solved by different agents. Explicitly modeling the underlying structural model can serve to clarify such estimation issues.

Suppose instead that the analyst is indeed interested in the structure of the decision process. For instance, with reference to our model of timber harvesting on NIPF's, the analyst wishes to know something about the price expectations held by NIPF owners. It is clear that reduced form estimation would not be adequate to address this question; estimation of the decision rule provides no insights to the underlying structure of the decision problem, and so its value as a policy tool is somewhat limited. For instance, in the case at hand the analyst would be unable to determine whether the price expectations of forest owners are rational, adaptive, or something else altogether, and so the reduced form model would provide no insight to the response of forest owners to changes in tax policy. Or consider the issue considered by MacNair *et al.*[3], the implicit price of the nontimber goods and services produced on national forests. The simple timber harvesting model presented above can be modified to consider the more complicated timber management decision supposedly made on national forests. For instance, if we once again assume that the only timber management decision is the harvest decision (here we make this assumption only for the sake of exposition), then the utility functions $u(s_t)$ can be modified to include additional relevant state variables, such as the distance to various aesthetic features such as lakes and streams, and a parametric version of $u(\mathbf{x}_{jt}, y_t)$ is then estimable upon structural estimation of the model using stand-level data. To reduce the complexity of the problem, those parameters identifiable from a simple revenue maximization model can be estimated separately using alternative data. Such parameters would include

[3] *MacNair, Douglas, and Thomas Holmes, Raymond Palmquist, and John Loomis. "A Public Choice Model of Forest Service Decison Making." Paper presented at the annual meeting of the American Agricultural Economics Association, Indianapolis, IN, August 1995.*

parameters associated with timber growth functions and timber price expectations. The possible sources of alternative data used to estimate this subset of parameters are several. One is the timber management models used by the Forest Service or other forestry professionals. Another is the professional judgments of consulting foresters. A third source is the timber management behavior of timber firms. The main point is that the complexity of the problem can be reduced significantly by recursive estimation of parameters. In any event, the estimated payoff function $u(\mathbf{x}_{jt}, y_t)$ is the value placed by the Forest Service on nontimber goods and services. Such values are simply not forthcoming from reduced form estimation of the decision rule used by the Forest Service in the harvest decision.

SUMMARY

To date, economic analyses of dynamic resource management problems has been largely normative, though the returns to such analyses appear to be small. This paper suggests that estimating even relatively simple models of dynamic decision problems can yield substantial insights to the forest management behavior of NIPF owners, timber firms, and government. The main obstacle to structural estimation of stochastic dynamic models is the computational complexity of such models. The dynamic decision problems resource managers and resource users *should* solve are typically understood to be quite complex, involving a large number of state variables. Direct estimation of such problems generally would require a large amount of high quality data, and access to a supercomputer. Yet it seems plausible that ultimately, normative considerations aside, resource managers are often guided by relatively simple rules-of-thumb which can be represented by fairly simple, albeit perhaps noisy, dynamic decision models. Reduced form estimation, which is best understood to be an attempt to estimate the decision rule emanating from a decision process, can serve as a diagnostic tool for identifying those state variables which are most important in the formulation of a structural model, but itself provides few insights relevant to public policy.

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ECONOMIC OPTIONS IN TROPICAL FOREST MANAGEMENT SUBJECT TO REGENERATION UNCERTAINTY

S. Rama Chandra Reddy and Colin Price[1]

ABSTRACT.—Natural regeneration is an important component of uneven-aged forest management. Tropical forests are subject to both commercial objectives of state and livelihood needs of population, assuming certain regeneration leads to intensive exploitation and degradation of forests in a stochastic environment. Regeneration uncertainty has major economic and ecological implications in tropical forest management. This study develops a stochastic model of ingrowth and analyses implications of regeneration uncertainty for tropical forest management. Management options—changes in cutting cycle, intensity of harvests, enrichment planting, and implications for plantation investment—are analyzed with a matrix model. Simulation based on long-term forest-level information from India is used to evaluate management options.

INTRODUCTION

Increasing realization of the importance of local (timber and nontimber products) and global (biodiversity and carbon storage) values of tropical forests has focused attention on rational management of tropical forest resources. Apart from their common role in timber supply, tropical and temperate forests differ in constitution, product flows, harvest regimes, and management policies. The features specific to tropical forests significantly affect their long-term sustainability (Panayotou and Sungsuwan 1994, Sandler 1993). The recent forest resource assessment in the tropics (Food and Agricultural Organization (FAO) 1993) corroborates the concern that degradation of tropical forests is more rapid than land use conversion through deforestation. It is urgent that the impact of regeneration uncertainty on forest management be analyzed. This study attempts to do so.

Many works have addressed the economic problem of steady state management in uneven-aged forests (Duerr and Bond 1952, Adams and Ek 1974, Adams 1976, Buongiorno and Mitchie 1980, Chang 1981, Nautiyal 1983, Haight and Getz 1987). Steady-state management assumes certainty in regeneration over an infinite period of time on the presumption that, once the stand is harvested, reduced stand density will allow regeneration in succeeding periods. This provides tractability in optimization. However, in the context of tropical forests, it may not give realistic later-period results. As most tropical forests are subject to rising demographic pressure, steady-state management results may be unrealistic, especially under uncertainty about regeneration. For our purposes, we assume regeneration uncertainty to result from both natural and human influences.

This paper explores the economic options available in management of tropical forest resources under such uncertainty. Section 2 reviews the role of regeneration in tropical forests. In section 3, a stage-structured matrix model with stochastic regeneration is presented. Economic options under regeneration uncertainty are explored for the tropical moist deciduous forests of northern India in section 4. Section 5 concludes with management strategies under regeneration uncertainty.

REGENERATION IN TROPICAL FORESTS

Regeneration is the basis of renewable resources, such as fisheries, forestry, whaling, wild game, etc. Empirical work in fishery economics has underlined the significance of stock recruitment relationships (Ricker 1954, Clark 1976, Parma 1990). Similar approaches have not received adequate attention in the context of tropical forest management, as testified by the limited number of quantitative studies on regeneration-related aspects of tropical forestry (Pande 1956, Seth 1961, Vanclay 1992). Possible reasons cited include land use changes manifesting adverse ecological influence on stand renewability (Uhl and Jordan 1984); rent-seeking policies of logging and inadequate investment in regeneration (Repetto and Gillis 1988); and the long-term nature of forest growth and its multiple products, favoring exploitation by local

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communities and governments with similarly limited interest in regeneration (Panayotou and Sunguwan 1994).

Three predominant uncertainties influence decisions of forest management: regeneration, stand development, and market prices. Previous research has focused on uncertainties in stand growth influenced by factors like fire (Reed 1984, Martell 1980), pests and diseases (Reed and Errico 1987), and growth processes (Kaya and Buongiorno 1987). Studies on price uncertainty (Brazee and Mendelsohn 1988, Haight 1990, Thomson 1992, Forboseh *et al.* 1996) focused on its possible impact on forest management decisions. No study until now has explicitly considered regeneration uncertainty in the management of forest resources. Some studies have assumed biological uncertainty to be small and ignored it (Haight 1990). In the context of tropical forests, regeneration uncertainty gains significance as loss of regeneration coupled with intensity of community dependence on forest products (Krutilla *et al.* 1995) leads to continued degradation of forests and their eventual conversion to open forests and other land uses. Hence, stand level management policies should explicitly include regeneration uncertainty in economic analysis so that adaptive management strategies may be formulated.

A combination of factors at stand level, like periodic seeding years, low and irregular germination and establishment rates, and variability in site, rainfall, and fire, along with management intensity of harvest of timber and non-timber products, significantly affect regeneration status. For example, Dipterocarp Sal (*Shorea robusta*) forests of the present study have periodic high and low seeding years and frost susceptibility of seedlings that have adverse influence on the regeneration status.

The regeneration behavior of forests may be grouped into:

1. Steady State: in these forests, natural regeneration adjusts to steady-state forest growth over a long period. Most studies in uneven-aged forests have assumed steady-state management and certainty in regenerative capacity (Duerr and Bond 1952, Adams and Ek 1974, Haight 1985, Ingram and Buongiorno 1996).

2. Cyclical: there are strong cyclical trends, with alternating periods of high and low regeneration.

3. Irregular: forests are characterized by irregular periods of abundant and scarce regeneration.

4. Spasmodic: forests regenerate vigorously, then collapse with or without major recovery.

Economic analyses of group 2 and 3 are in preparation, while the present paper analyzes spasmodic regeneration (group 4), in the framework of duration analysis. Possible economic implications are explored through the stage-structured growth model with a stochastic regeneration function.

STAGE-STRUCTURED GROWTH MODEL

The stage-structured growth model is an extension of a Leslie-type matrix (Leslie 1945, Usher 1966) with replacement of age classes by stage or diameter classes. The model uses density-dependent regeneration, growth, and mortality functions. The stand diameter distribution of trees at time period t is given by $x(t)$ and the harvest is represented by the vector $h(t)$. During a specific growth interval θ, the processes affecting the forest resource are regeneration of trees $k(t)$ into the lowest diameter class, growth, mortality, and harvest, which may all be represented by a different equation of the following form:

$$(1.1) \qquad x_{t+1} = G[(d_t)(x_t - h_t) + d_t \underline{k}]$$

where:

$x_{i\,t}$ = trees in diameter class i at time t
h_{it} = control variable of trees harvested between t and t +1
k_n = function of natural regeneration ingrowth
G = n-dimensional matrix composed of density-dependent functions representing transition probabilities: r_{1j}, probability of trees remaining in the same diameter class; $g_{ij,}$ probability of transition into the next diameter class during growth interval t+1; m_{ij}, probability of mortality in each size class, given by $[1-r_{ij} -g_{ij}]$; and d(t), vector of stand density variables influencing regeneration, growth, and mortality.

Data

Forest inventory information from the tropical moist deciduous forests of northern India was considered for detailed analysis. Twelve permanent sample plots measured at 5- and 10-year intervals between 1936 to 1996 formed the data base for the study. The data presented are for all-aged forests of site quality 2, the predominant species being *Shorea robusta, Terminalia tomentosa,* and *Adina cardifolia.* The three major species form 80 to 90 percent of total stand basal area. Data on these species are used in the analysis, and scaled up for noncommercial species. Transition matrices were estimated using tree-level information for a minimum diameter of 20 cm at each inventory. The 60-year forest level information was used to analyze regeneration uncertainty. The longitudinal nature of the data set provides some confidence in the results: no previous study has, to our knowledge, considered such inventory

data in analyzing regeneration uncertainty and its economic implications.

Stochastic Model of Regeneration

Analysis of the permanent sample plots over six decades indicated that regeneration does not merely follow density-dependent relationships: there is steady decline in regeneration, regardless of changes in forest density. Tropical forest inventory analyses indicate that regeneration is highly variable and stochastic (Vanclay 1992). When stochastic regeneration is analyzed as duration data, the variable of interest may be treated as failure time data. In the analysis of failure time data, survival and hazard functions assume significance (see Jhonson and Jhonson 1980, Kalbfleisch and Prentice 1980, Keifer 1988). The survivor function, which denotes the probability of regeneration surviving to the inventory period *t*, may be given by:

$$(1.2) \quad S_{(t)} = \exp[-\int_{o}^{t} \lambda(t)\, dt]$$

Where $\lambda(t)$ is the hazard function denoting the conditional probability of recruitment and may be given by

$$(1.3) \quad \lambda(t) = \lim_{\_t \to 0} \frac{P(t \le T < t + \_t \mid T \ge t)}{\_t}$$

For the estimation of survivor and hazard functions of recruitment to lowest diameter class, the two-parameter Weibull model was considered.

Weibull Distribution

The two-parameter Weibull probability density function is denoted by

$$(1.4) \quad f(t) = (ct^{c-1}/\beta^{c}) * \exp(-(t)/\beta)^{c}$$

The cumulative proportion of recruitment up to period 't' may be given by the cumulative density function

$$(1.5) \quad F_{(t)} = 1 - \exp[-(t/\beta)^{c}]$$

The probability of recruitment as a survival function $S_{(t)}$ is given by

$$(1.6) \quad S_{(t)} = \exp[-(t/\beta)^{c}]$$

where t is the period of inventory, and β and c are scale and shape parameters of the model.

The parameters of the recruitment function were estimated with the Weibull model and may be written as:

$$(1.7) \quad S_{(t)} = \exp[-(t/3.80513)^{1.96334}]$$

(0.38444) (0.480797)

R squared=0.96386 N=72

The figures in the parentheses are standard errors. The close conformity of predicted and observed values of distribution ($t < 0.01$) and high coefficient of multiple determination (R^2) support the adequacy of the model.

Hazard Function of Recruitment

As noted above, the hazard function is the instantaneous mortality rate of conditional distribution and may be given by

$$(1.8) \quad \lambda_{(t)} = f_{(t)} / (1 - F_{(t)})$$

The hazard function of recruitment under the Weibull model may be given as

$$(1.9) \quad \lambda_{(t)} = (c/\beta)(t/\beta)^{c-1}$$

For c=1, the Weibull model of recruitment will follow the exponential form with a constant hazard rate, caused by continuous decline in regeneration and conversion to open forests of low crown cover density, under high demographic pressure where forests are subjected to exploitation near habitations. Based on the estimated parameters of Weibull distribution, the hazard rate of recruitment for individual plots and as well as for pooled data were estimated between the periods.

Stand Projection with Stochastic Regeneration

Stand projection was undertaken with stochastic regeneration and alternative scenarios. The regular harvest regimes under stochastic regeneration may lead to forest loss instead of encouraging regeneration. Hence, unlike the passive strategies of maximizing the harvest for a given steady state, active or feedback strategies under regeneration uncertainty aim at maximization or conservation of residual stock. Stochastic optimization may enable investigation of management strategies under regeneration uncertainty. However, due to constraints of computational time, simulation of alternative strategies is attempted here.

ECONOMIC IMPLICATIONS OF REGENERATION UNCERTAINTY

Historical data on tropical forest resources often reveal gross uncertainties about the sustainable yield, optimum harvest levels, and investment in regeneration improvement. These uncertainties are due to our fundamental lack of experience about how the stock behaves under alternative measures. Under uncertainty, how should

management respond when the optimum can only be found by testing alternative possibilities through management experience? In the face of large uncertainties, forest management is necessarily an adaptive process where developing decisions and policies may profoundly influence how rapidly uncertainties are resolved. The fact that management is adaptive raises two key issues:

1. How can we model the impact of different decision choices on uncertainty, recognizing that decisions made today will lead to uncertainty for future stock assessment and decision-making?

2. How should management policies be adjusted to take into account the value of information associated with decision choices that may help resolve future uncertainties?

For a risk-averse decision-maker, it is pertinent to analyze the possible implications of changing forest density and growing stock at stand and regional levels. Studies on management strategies in uneven-aged management may be grouped into passive adaptive or deterministic optimization studies (Adams and Ek 1974, Buongiorno and Mitchie 1980, Haight 1985). Passive adaptive policies may work when uncertainties are small. For major uncertainties, active adaptive strategies or feedback policies acquire significance (Lembersky and Johnson 1975, Kaya and Buongiorno 1987, Haight 1990). The following adaptive management alternatives are explored in the context of regeneration uncertainty:

1. Salvage harvest

2. Reforestation and differential harvest
   a) Changes in cutting cycles
   b) Changes in harvest intensity

3. Afforestation using substitute plantations as insurance against regeneration uncertainty

Salvage Harvest

The salvage harvest option assumes that the future regeneration does not respond adequately to density changes and management has only the option of prolonging stand life by salvage harvest of mortality. Salvage is undertaken at 10-year intervals. Table 1 presents the salvage value of the stand. Probabilistic simulation of stochastic regeneration was done to assess convergence of the harvest value. Under extreme regeneration loss, salvage is one option to support the residual stand density, with the expectation of future regeneration when favorable conditions return. In the salvage harvest option, the equality of marginal revenue product and marginal input cost of growing stock investment (Chang 1981) may not hold. Hence the present value of salvage is estimated as an outflow or byproduct of stand growth. The present value of salvage harvest is

(1.10)

$$S_t = \Sigma_{i=0}^{160} \delta_t [(p' h_s f)]$$

where:
p' = price vector per m^3 of salvage timber
h_s = harvest vector of mortality
f = Costs of harvest (Rs./m^3)
δ = Discount rate

Table 1.—*Salvage harvest option*

Variable	Units	10 year stand projection (2006)	160 year stand projection (2156)
Stand Structure in number of trees per ha	**Mid dia. class (cm)**		
	25	34.5	20.0
	35	39.2	21.7
	45	37.2	21.2
	55	27.1	18.3
	65	11.5	13.9
	75+	3.8	14.3
Total number of trees per ha	N/ha	153.3	109.4
Basal area	m2/ha	23.31	21.87
Value of residual stock	Rs000/ha	1329.25	1345.99
Expected Present Value (%)	Rs000/ha		
1		52.76	297.52
2.5		49.32	143.37
5.0		44.69	76.44
7.5		41.23	55.55
10		38.37	45.87

Table 1 clarifies that the stand structure over 160 years assumes a right-skewed distribution with predominance of old trees in comparison to the original inverse-J distribution of 1936. As the upper diameter classes grow, basal area and value of residual growing stock increases. The salvage harvest option may be economical for a period of about 160 to 200 years; however, high fixed costs of extraction may make salvage harvests prohibitively expensive, and the course left to cash-limited management is to abandon the stand. Traditional NPV maximization may promote clearance of the existing forest and replanting, since clearcutting will yield a lump sum for reinvestment in regeneration. However, the opportunity cost of clearcutting may be losing two options:

1. Traditional forest composition and associated nontimber values (these aspects are not considered here, but are under investigation).
2. Future natural regeneration, if favorable condition return.

Differential Harvest Regimes and Reforestation Option

Under regeneration uncertainty, a possible option is intermittent harvests with reforestation of the stand. Table 2 shows the results of reforestation at 40-year intervals at a harvest intensity of 20 percent in the selection diameter classes (≥50 cm). Reforestation with various harvest intensities is practiced in the low-density forests of South and Southeast Asia under various names: enrichment planting, density improvement, rehabilitation forestry, etc. The difference equation of the growth model (equation 1.1) may be rewritten to include reforestation with the same species through enrichment planting:

$$(1.11) \quad x_{t+i} = G[(d_t)(x_t - h_t) + d_t\underline{k} + \underline{r}]$$

where r is the vector of reforestation at 40-year intervals.

As new recruits take about 40 years to enter the 20 cm diameter class, a reforestation initiative occurs at this interval. The assumption is that planting 1,000 seedlings in year 0 provides regeneration of 25 seedlings into the lowest diameter class by year 40. It is also assumed that future harvests consider the progress of reforestation. This assumption safeguards against harvest of existing residual stock. Comparison of 20- and 40-year cutting cycles indicated that the residual stock was higher under the 40-year cycle. Another key consideration is logging damage to the residual stock on the 20-year cycle. On these criteria, a 40-year cycle is preferred as it allows establishment of reforested seedlings and avoids periodic logging damage to young stock (not included in our calculations).

Afforestation Option of Substitute Species as Insurance

Under spasmodic regeneration, afforestation is an important option when selection forests fail to respond to

Table 2.—*Cutting cycle of 40 years with 20 percent harvest intensity in selection diameter classes (50 cm+) and reforestation at 40-year intervals*

Variable	Units	40-year stand projection	160-year stand projection
Stand Structure	Mid dia. class (cm)		
in number of	25	55.9	60.5
trees per hectare	35	31.8	35.9
	45	28.6	30.7
	55	14.2	13.1
	65	8.1	6.6
	75+	4.4	4.6
Total trees	N/ha	143.1	151.3
Basal area	m2/ha	18.37	18.63
Value of residual stock	'000 Rs/ha	999.94	996.71
Expected present value (%)	'000Rs/ha		
1.0		433.05	720.47
2.0		332.81	395.35
5.0		255.63	261.64
7.5		226.61	227.06
10.0		215.44	215.36

the above management treatments. The investment in afforestation option is proportional to the rate of substitution of plantation timber from the selection forests. In our case, the afforestation option of teak (*Tectona grandis*) is illustrated as it forms a major component of afforestation in India; plantation-grown teak is increasingly being substituted for the timber from natural forests. It is grown for its structural use and high value. The afforestation option is presented with the assumption that selection forests are managed only for salvage harvests, while commercial timber is harvested from teak plantations on a 40-year rotation. Timber obtained on this rotation can replace timber of 30-40 cm diameter size class from selection forests. For higher diameter classes, a rotation of 60 years or more is needed. The 40-year teak rotation safeguards against timber harvests from the pole and small timber classes of natural forests by local inhabitants. Table 3 presents the economic value of selection forests with regeneration uncertainty managed for salvage harvests and teak afforestation undertaken with a 40-year rotation to provide substitutes for small timber.

CONCLUSIONS

Regeneration uncertainty has significant long-term implications for management of tropical forests. Harvest strategies aimed at steady-state management may mine the residual standing stock. Under uncertain regeneration, possible strategies include salvage management, abandonment, reforestation, and plantation investment. The policies chosen for stand and regional forest management depend upon the information on regeneration, which can only be obtained through repeated forest inventory. The lack of an organized inventory network constitutes major constraints in many tropical countries. The tropical forest assessment recently initiated by Food and Agricultural Organization (FAO) focuses on regional level forest changes. To address the problem of degradation resulting from regeneration uncertainty, the FAO assessment needs to incorporate a mechanism for regeneration assessment across the tropics. With availability of the regeneration status of forests, it is possible to initiate management measures. The current debate on sustainable forest management also provides justification for the focus on regeneration uncertainty and the resultant policies of stand and forest conservation.

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Table 3.—*Management of selection forest with salvage harvests and afforestation option with teak (*Tectona grandis*) with 40 year rotation*

Variable	Units	Stand projection with salvage management 2036 (40 yrs)	Afforestation with teak (*Tectona grandis*)
Stand Structure	Mid dia. class (cm)		0 yr—2500 plants
in number of	25	33.1	3 yr—2200 @ 88%survival
trees per hectare	35	33.5	5 yr— 720 thin
	45	33.4	10 yr—673 thin
	55	26.4	20 yr—484 thin
	65	14.9	30 yr—148 thin
	75+	7.5	40 yr—165 Clear Fell
Total trees	N/ha	143.1	165 at year 40
Basal area	m2/ha	18.37	15.02
Value of residual stock	Rs000/ha	999.94	1184.6 (at year 40 before clear felled)
Expected present value (%)	Rs000/ha		
1.0		123.84	845.54
2.0		95.01	696.96
5.0		67.98	575.33
7.5		53.62	187.45
10.0		45.36	30.67

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PASSIVE FROST-RISK REDUCTION FOR FOREST MANAGEMENT IN NORTHERN HARDWOODS

Brian E. Potter[1]

ABSTRACT.—Observational data and an atmospheric radiation model were combined to examine nocturnal cooling in a northern hardwood forest. The model provided a mechanism for examining which properties of the forest and atmosphere play a significant role in preventing radiative freeze or frost events. The results of the simulations suggest that site basal area exerts some control over heat loss, with higher basal areas providing more heat retention than lower basal areas. This information is extended in the form of maps for Minnesota, Michigan, and Wisconsin indicating the amount of basal area needed to protect against the magnitudes of late spring freezes historically experienced in different locations.

INTRODUCTION

When a forest experiences a late spring frost or freeze, some plant species suffer more than others. Oak and walnut are two examples of economically valuable trees that suffer from frost. Frost or freezing temperatures may kill the leader, leaves, or flowers. This mortality in turn affects regeneration and tree form. Because of these detrimental effects of frost, frost prevention can be a useful tool in forest management: it may not make or break a management plan in itself, but it can give desired species an advantage and allow more seedlings to survive other types of attack or disturbance.

There are two general types of freeze that can occur in a forest in late spring. One is an advective freeze, where cold air moves into the forest from another area. Cloud cover, strong winds, and precipitation may accompany an advective freeze. While temperatures drop below freezing, frost does not usually form on the ground. The arrival of a Hudson Bay air mass is often responsible for late spring advective freezes in the Lake States. In areas with significant topographic relief, drainage of cold air from exposed ridges may also produce freezes in low-lying areas. Because the cold air in an advective freeze comes from another location, managing a forest in a way that prevents all advective freezes is difficult or impossible.

The second type of freeze is a radiative freeze, in which radiative cooling of the ground at night cools the air immediately above it below the freezing point. A radiative freeze requires calm winds and is most common under clear skies. When the ground cools below the dewpoint, frost forms. As the night proceeds and temperatures continue to drop, the pool of below-freezing air may deepen to a meter or more. A radiative freeze may kill seedlings and leaders but will not usually affect flowers on taller, more mature trees. Because the cooling occurs locally, it is possible to take measures in a forest to reduce the risk of frost near the ground.

There are two principal ways by which forests reduce the risk of radiative freeze. One relies on the canopy foliage, which blocks radiation traveling upward from the ground and prevents the energy from escaping. The second results from the amount of heat stored in the trees and other vegetation. A given volume of wood, leaf, or rock at any temperature contains more energy than an equal volume of air at the same temperature. For this reason alone, more vegetation on a site provides protection against more severe radiative freezes. This is true whether or not leaves are on the overstory trees. While the former mechanism is often acknowledged in "conventional wisdom" and forest meteorological literature (e.g., Kittredge 1948, Geiger 1965, Wales 1967), the latter has been largely neglected or ignored. One reference in Geiger (1965) alludes to the fact that nocturnal cooling is reduced in leafless forests, but attributes this to trunks of trees blocking the outgoing radiation, not to their greater heat capacity and slower cooling.

I have used computer simulations of radiative energy transfer in the atmosphere, in conjunction with field data from three coterminous forest sites, to determine a relationship between heat storage in a forest and basal area. I then used the same model and the derived

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relationship to assess the amount of protection a given amount of basal area provides against potential frost. The results of this latter analysis provide guidance in determining how much vegetation one can remove from a site without unduly risking frost damage.

METHOD

Observational Data

In 1993, USDA Forest Service researchers installed meteorological instruments in three adjacent forest plots at Willow Springs on the Chequamegon National Forest near Park Falls, Wisconsin (fig. 1). White ash, sugar maple, basswood, and red oak are the dominant species in the plots. The canopy top is approximately 20 m above the ground. In 1988, the researchers clearcut one plot, removed half of the overstory from a second plot, and left the third plot uncut. The basal areas measured in the clearcut, half-cut, and uncut plots were 0.0, 17.0, and 32.4 m^2 ha^{-1}, respectively. Teclaw and Isebrands (1993) describe further details of the study site. The instruments in each plot measure and record air temperatures, humidities, and winds every hour at several heights between 0.25 m and 10 m. Further observational data used for verification in this study came from a field experiment currently underway at Helen Lake in the Sylvania Wilderness Area of the Ottawa National Forest (fig. 1).[2] The Helen Lake site is unmanaged old-growth forest, dominated by sugar maple, ironwood, and yellow birch. It is substantially different from the Willow Springs site in this respect; it also has a higher canopy top (roughly 28 m).

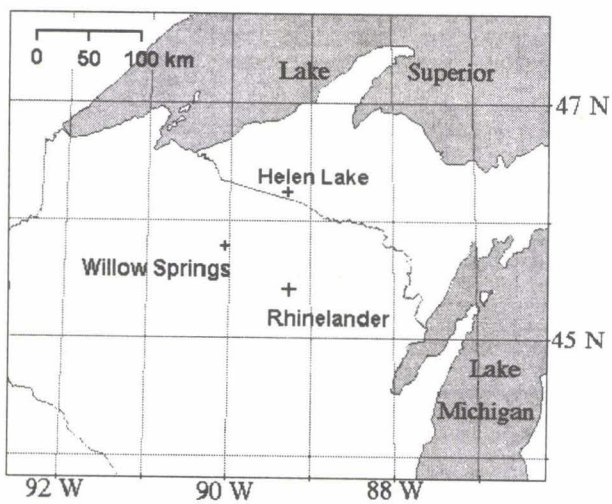

Figure 1.—*Map of northern Wisconsin and Michigan's Upper Peninsula, showing source locations for the meteorological data used in this study.*

[2] *Tom Crow, Project Leader, North Central Research Station, Rhinelander, WI. Personal communication.*

Simulations

I selected 27 nights from 1994 for simulation with an atmospheric model, based on both hourly observations in the clearcut and surface observations at nearby Rhinelander, WI. These nights all showed little or no wind as measured in the clearcut and steady cloud cover without precipitation as recorded at Rhinelander. I then initialized an atmospheric infrared radiative transfer model (Liou *et al.* 1984) using the temperatures and humidities measured on these nights in each of the three sites. The model calculates atmospheric and ground-surface temperature changes based on water vapor content, temperature, and specific heat[3] of individual layers of the atmosphere. It also calculates condensation or evaporation for each layer, as appropriate, to maintain thermodynamic equilibrium. By minimizing the model's error in reproducing observed temperatures through each of the nights at each plot, I determined a statistical relationship between plot basal area and specific heat.

I used the derived relationship to compute a value of specific heat for each plot at Willow Springs, and resimulated all of the 1994 nights using these computed values. From these resimulations, I then derived an expression for model error at a height of 0.5 m as a function of basal area.

Verification

Since derivation of the relationship between basal area and specific heat used only three stand densities, I assessed the usefulness of the relationship with an independent set of observations. For this purpose, I selected 23 nights (again with little or no wind, and steady cloud cover without precipitation) from the 1995 data at the Willow Springs and Helen Lake sites. I simulated these nights using specific heats obtained from the regression relationship, and examined the temperature errors from the simulations.

Extension

Next I used the radiative model to simulate a number of hypothetical nights with varying initial atmospheric conditions. For each night, I used the model to simulate five different values of basal area (one being clearcut, or basal area = 0). I then computed differences between final temperatures at 0.5 m from the clearcut simulations and each of the other four basal areas for a given night. By averaging these temperature differences over all nights for a given basal area, I obtained mean values of the amount of temperature protection provided by that

[3] *Specific heat is the amount of energy required to raise the temperature of 1 kilogram of a substance 1° C.*

basal area. Linear regression of the temperature differences as a function of basal area then provided a statistical relationship between the two quantities.

Application

Using 1961-1990 daily maximum and minimum temperature data for Michigan, Minnesota, and Wisconsin, I determined average freeze temperatures for freezes following growing degree day (GDD) accumulations of 250 and 300 degree days, base 5° C. I chose these GDD accumulations based on observations of frost damage to actively growing red oak and white ash seedlings at the Willow Springs sites in 1994.[4] From the freeze temperatures and the statistical relationship between temperature protection and basal area, I generated maps of the basal area required to protect against freeze conditions typical of a given location after a given degree day accumulation has been reached.

RESULTS

Table 1 summarizes the results of the optimization simulations. The large standard deviations reflect several important considerations. Foremost of these is the variability in the amount to which radiation dominated each night. Even though nights were carefully selected for the simulations, the selection criteria allowed for some degree of advective temperature change. The second factor influencing the standard deviation is soil moisture, which varies from day to day in a plot and which the model does not consider. The third important consideration is that the model results are somewhat insensitive to the exact value of the specific heat (c_f). Temperature errors for any given simulation vary by less than 0.01° C for values of c_f over a range of roughly 100 J kg^{-1}° C^{-1}. The root-mean-square (rms) temperature errors for the simulations are comparable for all plots, although they show some decrease as basal area increases.

Based on these average values, linear regression of c_f as a function of basal area (*ba*) yields the equation

$$(1) \quad c_f(ba) = 1140 + 109*ba,$$

with a correlation coefficient of $r^2 = 0.98$. As mentioned earlier, this relationship derives from only 3 data points, and requires independent verification. To produce a standard for comparison with the 1995 Willow Springs and Helen Lake dates, I resimulated the original sample of 1994 Willow Springs nights using values of c_f calculated from equation 1 for each plot. The average rms error for these simulations was 2.2° C. The rms errors from the verification tests using 1995 data are comparable: 2.3° C for the 1995 Willow Springs simulations and 2.6° C for the Helen Lake simulations.

Table 1.—*Summary statistics for optimization simulations. The parameter δT_{rms} is the rms error for the model compared to observations.*

Plot	c_f average ± standard deviation	δT_{rms} °C
Clearcut	1,004 ± 0	1.38
Half-cut	3,120 ± 1,780	1.36
Uncut	4,300 ± 2,100	1.26
Both forested sites	N/A	1.31

The radiative transfer model was next used to simulate 432 different scenarios. Each scenario used a unique combination of atmospheric moisture (q), sunset temperature (T_s), canopy height (z_c), atmospheric temperature gradient (Γ), and *ba*. The latter variable was reflected in the model as c_f, based on equation 1. I determined realistic ranges for each variable based on physical constraints and the 1994 Willow Springs observations. Table 2 shows the values of the five variables that I tested.

Table 2.—*Values of parameters varied in idealized simulations of nighttime cooling*

Parameter (units)	Test values
q (g kg^{-1})	3.0, 4.0, 5.0
T_s (°C)	3, 6, 9, 12
z_c (m)	16, 24, 32
Γ (°C km^{-1})	-50, 50, 150
ba (J kg^{-1} $°C^{-1}$)	0, 8.6, 17.3, 25.9, 34.5

For each chosen value of *ba*, I computed a temperature protection value, T_{prot};

$$(2) \quad T_{prot}(q, T_s, z_c, \Gamma, ba) = T_{final}(q, T_s, z_c, G, ba) - T_{final}(q, T_s, z_c, \Gamma, 0),$$

where T_{final} is the temperature at 0.5 m at the end of the simulation. This represents the difference in cooling between a clearing and a forested area, given the same initial moisture and temperature profile as well as some value for canopy height in the forested area.

By holding one variable (hereafter referred to as *x*) constant and averaging over all other variables, I assessed the sensitivity of the model to *x*. The difference between the average T_{prot} values corresponding to the

[4] *John Zasada, Project Leader, North Central Research Station, Grand Rapids, MN. Personal communication.*

extreme for x shown in table 2 indicates the comparative importance of x in controlling nocturnal cooling. Since several of the variables can vary over slightly wider ranges than those tested and shown in table 2, I determined more extreme maximum and minimum values, and extrapolated the results from table 2 to these new values. Table 3 shows the differences in T_{prot} across these wider ranges. Clearly, Γ has only a very weak influence. Canopy height, sunset temperature, and atmospheric moisture are an order of magnitude—almost 2 orders of magnitude—stronger, and all comparable to one another. Basal area has the strongest influence, roughly 3 times these other quantities. Furthermore, basal area and canopy height are the only parameters that both appear to have a significant impact on radiative cooling and can be manipulated in any real sense by people.

Table 3.—*Influence of various parameters on nocturnal radiative cooling*

Parameter (units)	Extreme values	Range of T_{prot} °C
q (g kg^{-1})	2.0, 5.5	1.1
T_s (°C)	3, 12	0.8
z_c (m)	10, 40	1.2
Γ (°C km^{-1})	-50, 150	0.02
ba (m^2 ha^{-1})	0, 50.0	3.0

I used the values of T_{prot} obtained by holding *ba* constant in this analysis in a linear regression to relate these two quantities. As a correction, I then applied the known model bias at 0.5 m, determined as a function of *ba* from the simulations of the 1994 Willow Springs data using c_f from equation 1. The final result is

$$(3)\quad T_{prot}(ba)=0.135*ba + 0.297, \qquad r^2=0.96$$

I examined National Weather Service daily temperature records for Michigan, Minnesota, and Wisconsin from the years 1961 to 1990, inclusive. Among the stations in these States, 133 have records that are 99 or 100 percent complete. These stations are all in open areas, away from buildings or other cover that might influence the measurements. By examining the daily maximum and minimum temperatures at these stations, I determined the dates each year on which a given station reached degree-day sums (base 5° C) of 50 through 350 at intervals of 50 degree days. To obtain average post-threshold freeze intensities, I averaged the temperatures of all freezes at a station after a given degree day threshold but before July 31 of each year. Using krigging for spatial interpolation, I mapped the freeze intensities following a given threshold for all 133 stations. Figure 2a shows an example of this, for the threshold of 300 degree days.

I then converted the maps of freeze intensity to maps showing how much basal area one would need to protect trees from the typical spring freeze at a location. This involved simply solving equation 3 for *ba*, and applying the resultant equation to the individual point values determined in the previous step. Figure 2b shows the subsequent map of protective basal area. It is clear from the figure that most locations in the these States considered require little basal area to provide the needed freeze protection.

The freeze climatology developed here employs temperatures measured at 2.0 m above the ground, usually in open areas. Equation 3, on the other hand, comes from model results at 0.5 m above ground. During a radiative frost, the 0.5 m temperature will be colder than the 2.0 m temperature because the frost is driven by ground cooling. Therefore, the temperatures in the freeze climatology are likely to be somewhat high with respect to what regeneration near the ground might experience. Typical temperature gradients between 0.5 m and 2.0 m suggest that the basal areas shown in figure 3 might be increased by 5 to 10 m^2 ha^{-1}.

CONCLUSIONS

The results of this study are based on one field experiment, which, in conjunction with the heavy use of a computer model, leaves their applicability over broad regions open to question. The present analysis is limited by observational data, and no amount of simulation or model adjustment can verify or refine the final results unless it rests on further observations from new field studies. Such a study, or studies, would need to examine a variety of ecosystems and vegetation densities in order to provide the widest base of input data for the model to work from.

The temperatures shown in figure 2a come from 99 stations in a broad geographic area. They do not reflect local or small-scale topographic effects in areas away from the stations. A forest manager concerned about such factors as drainage winds from ridges, or dry, sandy soil prone to frost development would need to subjectively adjust the protective *ba* shown in figure 2b. In spite of the need for further data, the field observations and model results both suggest that forest managers can reduce the risk of frost in a stand by maintaining a certain amount of basal area on the site. The amount of basal area required depends on location and the physiology of the species of interest. Finally, figures 2a and 2b represent the results for one specific degree-day threshold,

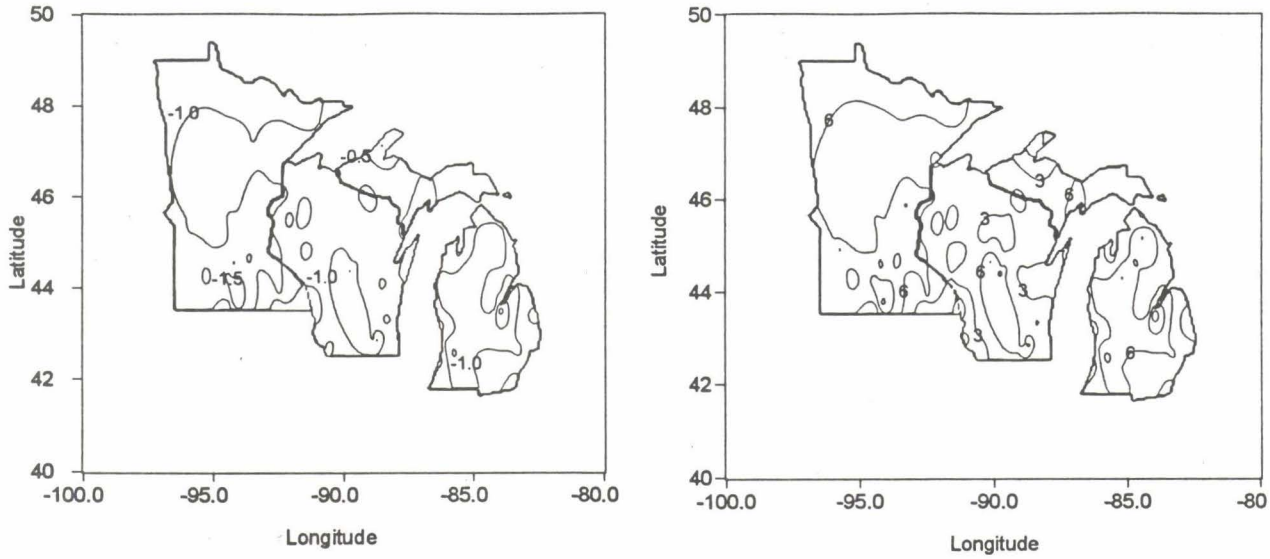

Figure 2.—*(a) Temperature of average freeze following 300 degree days, base 5° C, contour interval is 0.5° C; minimum values are –1.9° C in south central Minnesota and -2.0° C below Saginaw Bay, Michigan. (b) Basal area to protect against temperatures in (a). Contour interval is 3 m^2 ha^{-1} with maxima of 12.7 m^2 ha^{-1} in south central Minnesota and 13.8 m^2 ha^{-1} south of Saginaw Bay, Michigan.*

with a given base. The same type of maps can be generated for other thresholds and bases, as needed for given species.

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HARVEST PLANNING WITH UNCERTAIN FUTURE PRICES AND DEMANDS

Simon Papps[1]

ABSTRACT. —Harvest planning involves making harvesting decisions over multiple time periods. Usually the demands and prices for a set of log products are known for the first period but are uncertain in later periods. The typical approach to this situation is to run a set of models to explore the effect of different price scenarios. This, however, explores only a small subset of all possible future outcomes and does not compute a plan that hedges against all scenarios. Stochastic linear programming models can do this but tend to be very large and therefore difficult to solve. This paper describes a stochastic forestry modeling system and discusses the use of decomposition to solve such models.

INTRODUCTION

Most forestry decision-making occurs under risk or uncertainty. Forestry's long production cycle exacerbates this problem. Uncertainties exist in the prediction of future growth and yields, the effect of outside influences (e.g., the risk of fire), and the marketplace. These predictions are at best guesses that are subject to error.

The problem examined in this paper is harvest planning and log allocation with uncertain future demand and prices. Spread throughout the forest estate is a number of candidate stands for harvest over a number of time periods. The yields from these stands are represented as different log product types that are sold to potential customers. Each customer specifies a set of demands. A demand represents a constraint on the volume of a set of log types for which an at-mill price will be paid. In a deterministic model, demands and prices are specified in advance for all periods. While the short-term prices and demands may be known, this is seldom the case for future time periods.

Traditionally some form of sensitivity analysis is performed to quantify likely scenarios. While this practice is useful, it explores only a small subset of all possible futures. A deterministic model based upon a single scenario also contains an implicit assumption of perfect information; i.e., the demands and prices for all periods are known in advance.

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In short-term harvest planning, a number of stands are scheduled for harvesting. One must then decide when it is economically desirable to harvest each stand. This decision is dependent not only on the current prices and demands for log products during that period, but also on future prices and what the future demand will likely be. It is likely that a shrewd forest manager will hedge against the future in the event of higher prices, lower prices, or changing demand. When the outcome of a decision becomes known, a recourse, or corrective action, can be made.

STOCHASTIC LINEAR PROGRAMS WITH RECOURSE

Recourse problems are staged problems where the decision maker alternates decisions with realizations of stochastic data. Decisions are made for the current stage given assumptions of the probability of future events, or outcomes. After these decisions are made, the actual occurrences of some stochastic events become known. Based on the previous decisions and the new information obtained, an optimal corrective action is taken as the next stage is considered. This process closely approximates real-life dynamic decision making. The solution of the Stochastic Programming with Recourse (SPR) problem gives the recommended strategy for every defined scenario.

Few papers have considered multistage recourse as forest estate models are typically large and do not incorporate uncertainty. Hoganson and Rose (1987) developed a decomposition technique for obtaining approximate solutions to stochastic forest planning problems. They specified complicating constraints as penalty terms in the

objective function by using estimates of the dual variables as penalty weights. They formulated the problem as a model with two stages—one representing the long run and the other representing the short run. The objective was to minimize the cost of producing the desired forest outputs where the future forest output levels were uncertain.

Gassman (1989) developed a multistage recourse model for finding logging levels to maximize value. The risk of forest fires or other environmental hazards, which might destroy a random fraction of the existing forest, was uncertain. In his paper, he made the following conclusions:

- stochastic models lead to more conservative harvesting policies than deterministic ones,
- the value of information increases as the discount factor increases, and
- the solution to the mean value problem (MVP), where expected values are substituted for stochastic elements, becomes more unrealistic with increasing discount rates.

Boychuk and Martell (1996) used multistage stochastic programming to investigate the risk of fire. Two outcomes were possible in each of the first four periods, representing a high and a low fire loss, after which the expected fire loss was assumed. They compared their SPR model with the MVP, where the fire loss in each period was the expected value. They concluded that the MVP consistently overharvests, risking the possibility of a future shortfall under some scenarios.

The Equivalent Deterministic Problem (EDP) is the linear program that describes the SPR problem. The number of possible scenarios depends exponentially upon the number of decision stages, although a stage may represent more than one time period. The EDP is roughly the size of the original problem multiplied by the number of possible scenarios. Therefore, stochastic programs can very easily become too large to solve. For this reason, SPR models are as an intuitive approach to uncertainty as long as the number of stages is small.

This paper describes the creation of the EDP in the FOLPI forest estate modeling system. It discusses the regular structure of these problems as well as possible decomposition techniques to solve them. It also describes a model based on Stochastic Benders' Decomposition (SBD) and compares he results with EDP and MVP.

BUILDING A DETERMINISTIC EQUIVALENT PROBLEM WITH FOLPI

FOLPI is a linear-programming-based, forest estate modeling system that has been used in New Zealand for over 10 years for forest management planning, log allocation, and forest valuation. It corresponds to a Model B formulation (García 1990), which is an extension of the Model II formulation originally proposed by Johnson and Scheurman (1977). García (1990) describes the FOLPI formulation. Manley and Threadgill (1991) discuss the use of log allocation by FOLPI for the purpose of forest valuation. FOLPI has had considerable use in short-term planning where it determines harvesting decisions for individual stands (Manley 1994). Recent use of FOLPI has incorporated process modeling where processing plant output is included within the modeling system.

There is an analogy between the concept of future price scenarios and the use of log allocation in FOLPI to optimize and satisfy the demands of different products from a set of origins to a set of destinations. Each future scenario may be represented by a set of destinations, demands, and prices. Only one scenario may come true, so each scenario has an estimated probability of occurring.

A deterministic equivalent formulation of an SPR problem in FOLPI can be built by assigning each scenario its own unique set of decision variables. An additional required set of constraints forces harvesting to be the same for scenarios with identical outcomes up until and including the period in question. These nonanticipative constraints are of the form:

$$y_{tij1} = y_{tij2} = \ldots = y_{tijn}$$

where y_{tijq} represents the area cut in period t of crop type i in age class j for scenario q. Scenario number n varies by problem and stage depending upon the information available for the current stage and the possible future outcomes.

EXAMPLE

It is assumed that the harvest planner is in a learn-demand-then-produce situation. For a given period t, the planner knows the exact demand for that period as well as the values for previous demands. The planner may conceivably be in a produce-then-learn-demand situation, where the setting of the harvesting level for period t must be decided before the demand is known. While the planner may not really know the exact demand at the start of the period, this information becomes available during the period and the planner can usually readjust harvesting levels if required.

There are three possible price outcomes in this example: high, medium, and low. Harvesting produces radiata pine logs of varying quality: pruned logs, A- and J-grade saw logs, poor quality saw logs, and pulp logs. Table 1 lists each possible price outcome for these logs.

Table 1.—*Price list by product and outcome (New Zealand dollars per cubic meter)*

Product	High prices	Medium prices	Low prices	Average
RAD PA	$220.00	$200.00	$160.00	$193.33
RAD PB	$150.00	$130.00	$100.00	$126.67
RAD AG	$130.00	$110.00	$90.00	$110.00
RAD JG	$110.00	$100.00	$80.00	$96.67
RAD RT	$70.00	$55.00	$45.00	$56.67
RAD PU	$40.00	$35.00	$25.00	$33.33

RAD = radiata pine; PA = pruned logs; PB = pruned logs; AG = A-grade saw logs; JG = J-grade saw logs; RT = poor quality saw logs; PU = pulp logs.

A set of possible future scenarios may be represented as an event tree. This is a diagram that branches off for each possible outcome at each stage. A three-stage (one stage equals one period equals 1 year) model might have an event tree like the one in figure 1 if the known prices for the current period (year 1) were the medium prices.

There is an equal probability of any outcome occurring in this example. This need not be the case; the sole requirement is that the conditional probability of all possible future outcomes sum to 1.

A decision has to be made as to how much of the remaining area is to be harvested in the final period. To make that decision, some value must be placed on the nonharvested area at the end of the model. Calculating this boundary value is common practice in forestry linear programming models and is used to minimize end effects when overharvesting of the forest occurs towards the end of the planning horizon. In this case, the boundary value is calculated from the land expectation value, the expected discounted net cash flow assuming average prices over infinite periods when there are no yield regulation constraints.

It is a credit to the flexibility of the FOLPI modeling system that a complex, stochastic, equivalent deterministic model can be created without much difficulty. The one drawback to using FOLPI in this way is that each scenario must carry its own unique set of harvesting and wood-flow variables. Many of these variables can be removed because of nonanticipative constraints. A model based on the event tree in figure 1 would require the values of harvest variables to be the same for all scenarios in year 1:

$$y_{1ij1} = y_{1ij2} = y_{1ij3} = y_{1ij4} = y_{1ij5} = y_{1ij6} = y_{1ij7} = y_{1ij8} = y_{1ij9} \ \forall i, j$$

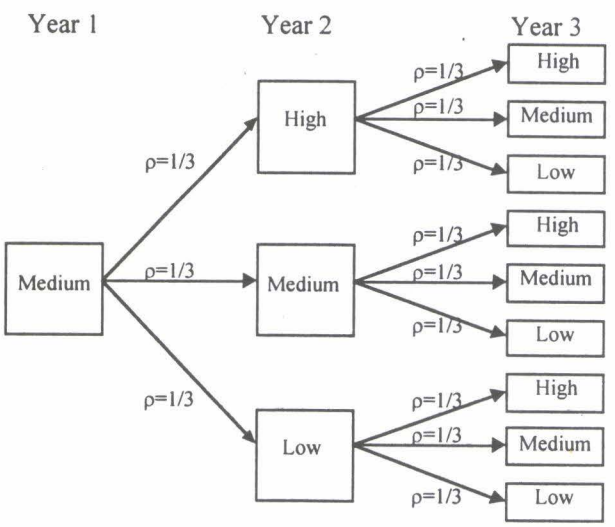

Figure 1.—*Event tree.*

Meanwhile, in period 2, the harvest variables would be the same for all scenarios that shared the same outcome for period 2:

$$y_{2ij1} = y_{2ij2} = y_{2ij3} \qquad y_{2ij4} = y_{2ij5} = y_{2ij6} \qquad y_{2ij7} = y_{2ij8} = y_{2ij9} \qquad \forall i,j$$

Those variables that are assumed to share equality can be merged into a single variable.

DECOMPOSITION

Although equivalent deterministic programs are large, they inevitably have a regular structure that can be exploited. The SPR model has a definite staircase structure where the nonanticipative constraints bind across stages (fig. 2).

A staircase structure by scenario is also possible by reordering of the constraints and variables.

STOCHASTIC BENDER'S DECOMPOSITION

Considerable promise has been shown for SBD, which has also been referred to as the L-shaped Decomposition Method (e.g., Kall and Wallace 1994). Each subproblem represents a possible outcome for a stage, i.e., a single node on the event tree. SBD is resource-driven: the ancestor subproblem explicitly allocates the resources and the subproblems find the best solutions. Variables are split into "hard" and "easy" sets. Due to the tightly coupled nature of the FOLPI structural constraints, it is not possible to separate the variables. The solution is to introduce state variables that describe the area in each period, crop type, and age class. This is a Model A (García 1990) "state space" formulation that considerably increases the number of variables but simplifies the form of the structural constraints. Reformulation of the FOLPI structural constraints makes the constraints as period independent as possible.

Let s_{tij} be the area at the start of period t in crop type I and age class j. SBD is based on the observation that given values for s_{tij} from the solution of the ancestor problem in period t-1, the decision problem can be written in the form:

$$\max \alpha_t \left(\sum_{i,j} C_{tij} s_{tij} + \sum_{p,f,d} R_{tpfd} u_{tpfd} \right) + Q_{t+1}(s)$$

subject to:

$$(1) \quad \sum_j y_{tij} = \sum_k r_{tik} \qquad \forall i$$

$$(2) \quad s_{1ij} - \sum_k z_{ijk} + \sum_k z_{kji} = A_{ij} \qquad \forall i,j \qquad \text{if } t = 1$$

$$(3) \quad s_{t+1,i,1} = \sum_k r_{tki} \qquad \forall i$$

$$(4) \quad y_{tij} + s_{t+1,i,j+1} = s_{tij} \qquad \forall i,j$$

(5) User defined constraints

$$(6) \quad \sum_d u_{tpfd} = \sum_{j \in f} V_{ijp} y_{tij} \qquad \forall p,f$$

$$(7) \quad \sum_{p \in l} u_{tpfd} = D_{tdl} \qquad \forall d,l$$

$$(8) \quad y_{tij}, s_{tij}, r_{tik}, z_{ijk} \geq 0 \qquad \forall i,j,k$$

$$(9) \quad u_{tpfd} \geq 0 \qquad \forall p,f,d$$

where:

$Q_{t+1}(s)$ = a concave function representing the present expected value of all possible future scenarios,

a_t = the discount rate in period t,

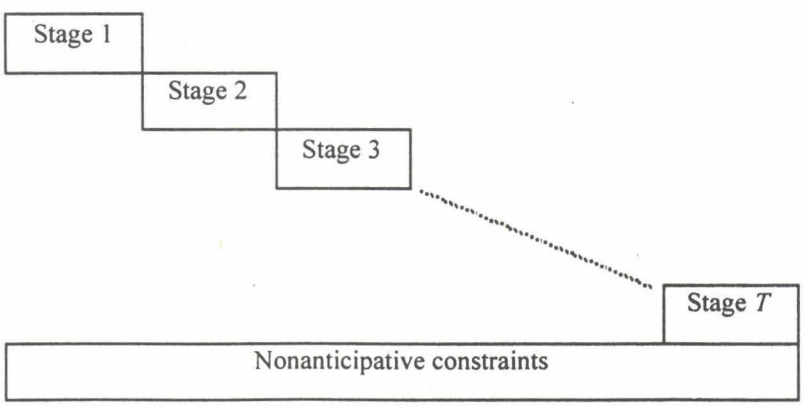

Figure 2.—*Staircase structure of the equivalent deterministic model.*

y_{tij} = area harvested of crop type i in age class j,
r_{tik} = area replanted from crop type i to crop type k,
z_{ijk} = area in age class j transferred from crop type i to crop type k at the start of the planning period,
u_{tpfd} = the wood flow of log product type p, from forest f to destination d,
A_{ij} = initial area in crop type i, age class j
C_{tij} = deterministic revenues and costs occurring during the rotation,
R_{tpfd} = the revenue gained from selling one unit volume of log product p from origin f to destination d,
D_{tdl} = the demand at destination d for l, a set of log product types p, and
V_{ijp} = the volume of log product type p produced by clear-felling one unit of area of crop type i, age class j.

Translated into words, these constraints state the following:

1. the area harvested must be replanted,
2. the area in a crop type and age class at the start of period 1 equals the area initially available, less the amount transferred out, plus the amount transferred into that crop type and age class,
3. the area in a crop type in age class one at the start of the subsequent period equals the amount replanted into that crop type during the current period,
4. the area for a given crop type and age class at the start of the subsequent period equals the amount of area in the current period and age class less the amount that was harvested during the period,
5. constraints on the forest resource representing restrictions placed on the resource by outside factors,
6. the wood flow to all destinations or customers for a forest and log product equals the sum of the volume of that log type cut from all crop types in that forest, and
7. the definition of the destination demands in the current outcome.

Constraint sets 3, 4, and possibly 5 are coupling constraints which reference solely the subsequent stage. This is a necessary restriction to simplify the SBD solution process; additional constraints defined by the user (5) cannot violate this restriction. This requirement is not too restrictive as user constraints usually set a bound for a period or constrain a resource between consecutive periods. The nonanticipative constraints are implicit in the decomposition and are unnecessary. The ancestor problem passes values for the s_{tij} variables to the current subproblem. These values are used as the right-hand side in constraint set 4.

The function $Q_{t+1}(s)$ is approximated by adding an unrestricted variable θ in the objective function. This variable is constrained by the addition of Benders' cut constraints, so that θ gives an upper bound estimate on the value of the subproblems for the stage.

It is easiest to explain the form of Benders' cut by considering a problem with only one state variable s (i.e., only one crop type and one age class) representing the amount of area passed down to a single subproblem beneath it. In this case, a revenue curve could be drawn representing the revenue earned (θ) versus the amount of area (s) passed down to the subproblem (fig. 3).

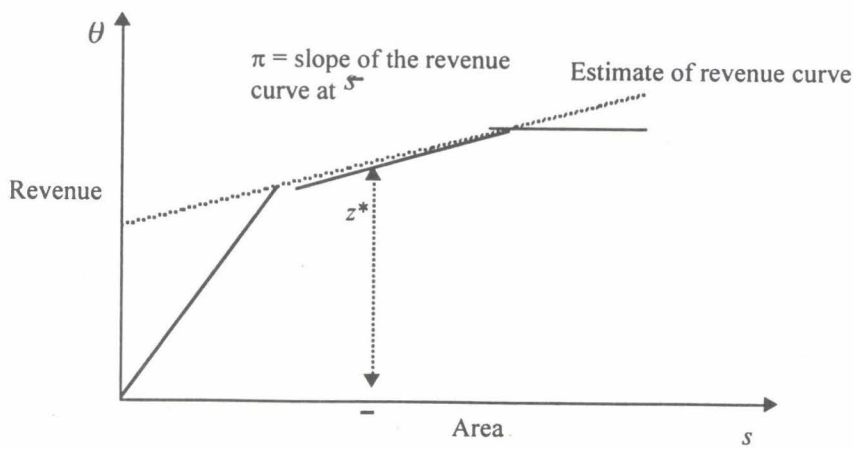

Figure 3.—*Revenue curve for state variable* s.

The actual form of this revenue curve is unknown. The only information available upon solution of the subproblem is

$\bar{s}$ the value of s passed down to the subproblem,

z^*, the objective function value of the subproblem, and

π, the marginal revenue at $\bar{s}$, i.e., the dual of the constraint in the subproblem with right hand side $\bar{s}$.

Given solely this information, the best estimate we can derive for θ is a straight line that gives a revenue of z^* at $\bar{s}$ and has slope of π. An estimate for θ is therefore $\pi s + (z^* - \pi\bar{s})$. Assuming that the revenue function over the allowable clear-felling ages is concave, our estimate for θ is an upper bound. As the subproblem is solved repeatedly with differing values for $\bar{s}$ the estimator for θ approximates the revenue curve more closely.

The upper bound gives an estimate for the value of subsequent periods by defining θ in terms of the areas passed down to the subproblems in the state variables $s_{t+1,i,j}$. Summing over all state variables and all possible subproblem outcomes ξ weighted by their probabilities gives the generalized Benders' cut:

$$\theta \le \sum_{\xi} \rho_{\xi} \left(z^*_{\xi} + \sum_{i,j} \pi_{\xi ij} s_{t+1,i,j} - \pi_{\xi ij} \bar{s}_{t+1,i,j} \right)$$

In summary, each problem passes down the area/age class distribution as right-hand side values $\bar{s}_{t+1,i,j}$ to its descendant subproblems. Upon solution, each subproblem contributes towards the formulation of an additional Benders' cut constraint that constrains θ with respect to the state variables $s_{t+1,i,j}$, giving an estimate of future value. After being solved again, the problem obtains a new value for θ, a new cutting plan for the period, and changes the initial area/age class distribution for the subproblems. Figure 4 shows the relationship between SBD subproblems.

Subproblems may be solved in any order providing the ancestor subproblem has been solved at least once. The algorithm terminates when the objective function value (including θ) for the period 1 subproblem is within a tolerance of the current solution (excluding θ) plus the nested sum of the probability-weighted solution values for all descendant subproblems. Initial harvesting plans for a period will be aggressive, as no consideration is given towards the potential future earnings of future periods. As Benders' cuts are added, the amount harvested for an outcome will tend towards a level that weighs harvesting at current prices against the opportunity of an additional year's growth, the effect of discounting, and the uncertainty of future prices. The optimal harvesting strategy will inevitably harvest as much as possible when prices are high, and as little as possible when prices are low.

RESULTS

The implementation of the SBD model was developed with the Watcom C++ compiler and the CPLEX Callable Library. Each solution was compared with the MVP and the EDP generated by FOLPI as Mathematical Programming System format files and solved by the CPLEX Simplex solver. Table 2 shows the results of this comparison.

Two forest resource descriptions were used:

- a one crop type model representing 300 hectares (ha) of radiata pine, which assumes that the entire resource grows and is managed the same way,

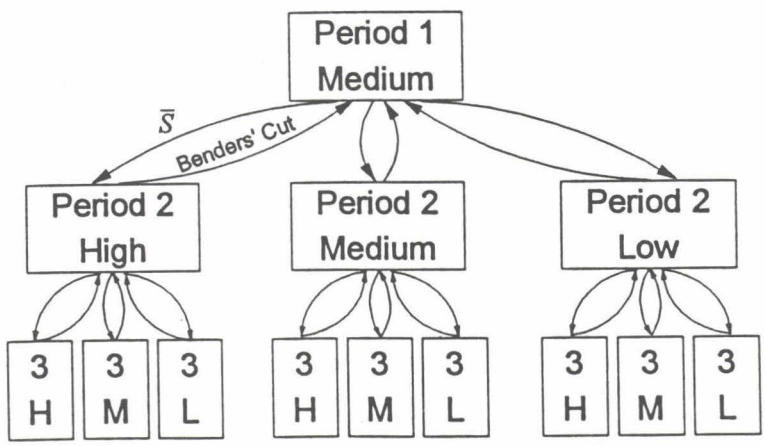

Figure 4.—*Relationship betweem SBD subproblems.*

- a forest resource of 9,406 ha described by 20 crop types, representing a heterogeneous radiata pine forest with differing growth and silviculture.

Three outcomes were possible in each period using the prices from table 1. An upper and lower bound was placed upon demand while a boundary value ensured that overcutting of the resource did not take place. The one crop type model could not harvest more than 50,000 cubic meters (m^3), while the 20 crop type model was required to supply between 100,000 m^3 and 500,000 m^3. A severe penalty ($500 per m^3) was placed on unsatisfied demand, so solutions feasible for all possible future scenarios were always found. The objective function value represents the expected future revenue as no costs were assumed in the model. A discount rate of 10 percent was used. This is high by international standards but not unreasonable for the New Zealand situation.

All except the four-stage models were solved on a 90 megahertz (MHz) Pentium with 32 megabytes (MB) of RAM running Windows NT. The four-stage EDP model used virtual memory that slowed solution time considerably. To ensure that the comparative solution times would not be skewed by disk paging, the four stage problems were solved on a Windows NT 200 MHz Pentium with 96 MB of RAM. The reasonable solution times indicate stochastic models represented by large forest resource descriptions are possible. The equivalent deterministic and stochastic Benders' models should yield the same objective function value: the solutions are identical, and the difference is due to rounding in the calculation of the boundary value.

The difference between the MVP and recourse models represents the benefit of hedging or the value of the stochastic solution. Although these models are simplistic, they nevertheless illustrate that the use of expected values, in an environment of volatile prices and flexible supply contracts, will underestimate the value of the resource.

The SBD models took longer to find an optimal solution than their EDP counterparts. This was expected and is a common complaint of decomposition algorithms. There is scope for improvement for solution times. Currently the system uses shuffle pass (as described by Jacobs *et al.* 1995) where subproblems are solved in their entirety before a Benders' cut is added to the current problem. This is intuitively less efficient than fast pass, where a single cut is made before control returns to the ancestor program, as shuffle pass concentrates its search in a possibly unprofitable area of the feasible solution space. Initial comparisons between the two methods indicate that the fast pass is only slightly faster. A possible approach for improving solution time is for every subproblem to generate its own unique Benders' cut for its predecessor rather than an aggregate Benders' cut over all subproblems. Another possible investigative area when subproblems become difficult to solve is the use of

Table 2. —*Comparison between Stochastic Benders' Decomposition, Mean Value Problem, and the Equivalent Deterministic Problem*

Solution method	Stages	Scenarios	Sub-problems	Crop types	Constraints	Variables	Non-zeros	Solution time	Objective function value
								min:sec	*NZ$*
MVP	2	3		1	9	15	42	0:01	8,245,539
EDP	2	3		1	154	219	624	0:03	8,452,583
SBD	2	3	1+3	1	93	96	131	0:04	8,452,541
MVP	3	9		1	10	19	52	0:01	8,263,365
EDP	3	9		1	428	409	1,823	0:05	8,643,842
SBD	3	9	1+3+9	1	93	96	131	0:06	8,643,827
MVP	2	3		20	129	278	859	0:09	256,113,552
EDP	2	3		20	3,314	5,778	11,541	1:36	256,809,888
SBD	2	3	1+3	20	1,748	1,775	2,190	1:40	256,809,394
MVP	3	9		20	149	356	1,169	0:10	254,577,313
EDP	3	9		20	5,957	10,187	23,717	3:56	271,486,944
SBD	3	9	1+3+9	20	1,668	1,699	2,068	4:27	271,486,594
MVP	4	27		20	169	437	1,496	0:08	251,667,659
EDP	4	27		20	22,212	13,040	65,069	5:52	253,969,772
SBD	4	27	1+3+9+27	20	1,729	1,775	2,170	8:20	253,778,114

NZ$ = New Zealand dollars; MVP = mean value problem; EDP = equivalent deterministic problem; SBD = Stochastic Benders' Decomposition

inexact cuts (Philpott *et al.* 1997) where an interior point method is used to find good, but not necessarily optimal, feasible solutions that will then be used to generate a Benders' cut.

The real advantage of SBD lies with its tractability. Very large models that cannot be solved as an equivalent deterministic model can be solved by SBD as only a single subproblem needs to be in memory at one time. The problem of solution time becomes less of an issue with the increased use of parallel and distributed computing. Subproblems can be assigned to separate processors and solved independently since the data flow between processors is small. Very large problems then become solvable within a short period of time.

CONCLUSIONS

SPR's become considerably harder to solve as the number of stages increase due to the exponential nature of the problem. On the other hand, computing power has also increased at a near exponential rate and new algorithms such as SBD have become available to exploit the special structure of stochastic programs.

A model has been developed that uses SBD to solve SPR models for harvest scheduling and log allocation. While this model does not yet find the optimal solution as quickly as the equivalent deterministic model, its tractability lends advantages when multiple processors are available or models become too large to fit into available memory.

The next stage is to apply this model to a practical New Zealand forestry situation. It seems likely that a harvesting plan from an SPR model will derive more value from the resource than a deterministic plan with expected values. Realistic demands and prices will be required before comparing the MVP with a SPR. A key part of this exercise will be the generation of scenarios to be evaluated. These scenarios will represent potential future markets described as a set of possible demands and prices by log product type.

The modeling system described in this paper could also be used to measure the effect of catastrophic risk, since a catastrophe is a possible future outcome with a small probability of occurrence.

ACKNOWLEDGMENTS

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IMPLICATIONS OF FOREST PLANNING REQUIREMENTS AND INITIAL RESOURCE SITUATION FOR FOREST SERVICE PRODUCTION LEVEL RISK

James B. Pickens and Peter G. Ashton[1]

ABSTRACT. —This article evaluates the impact of Forest Service planning requirements on the degree of variability associated with periodic harvest targets. It is concluded that the temporal and spatial dispersion harvest requirements provide a degree of portfolio diversification that tends to reduce the variability associated with cutting period harvests. The reduction in variance depends on the "green-up" period, which determines how many cutting periods the harvest of an analysis area must be spread over, and the correlation between harvests across analysis areas. Longer green-up periods tend to spread harvests within an analysis area over more time and reduce harvest level variability, while positive correlations between analysis area yields would increase variability.

INTRODUCTION

The Forest Service (FS) of the United States Department of Agriculture manages forest and rangeland across the United States. It is very important that future timber harvest levels from these lands be predictable because many communities and industries in rural areas are highly dependent on the fiber harvested from FS lands. Unfortunately, there are several factors that dramatically reduce the accuracy of future harvest predictions.

Much uncertainty results from the inherently political environment in which the FS conducts management. This uncertainty is extremely difficult to foresee and respond to because of the relatively short-term nature of the political process, which can be measured by the period between elections, and the long-term nature of forest planning and management. Within the political system, we know well neither the possible future issues nor the probability that those issues will adversely impact planned timber harvest targets.

The prospects for adaptive management approaches in response to another major source of risk, the inherently random fiber production response of the managed forest ecosystem, are much more promising. The growth and development of forests are relatively well understood. Statistically derived growth and yield models providing both the expected production and the anticipated variability for most important forest communities in the US, and more precise information becomes available both through research and observed results of management actions over time. Furthermore, techniques for using single-stand production information to evaluate production level risk associated with implementing a specific harvest schedule at the forest level are available (Hof *et al.* 1995).

Another related issue is the implications for harvest level risk (variability) resulting from regulations and existing conditions when forest plans are developed. While the results presented by Hof *et al.* (1995) are only applicable to a single forest with the specified harvest schedule, estimation of the implications from planning characteristics have much broader applicability. This paper presents the results of a study to evaluate the impact of certain forest plan requirements and initial land base age structure on timber harvest risk (variability).

BACKGROUND

Many critical information needs, where the data is currently not known precisely, are encountered during the process of strategic planning by the FS. This missing information can be divided into two categories, **risk** and **uncertainty**, depending on our degree of understanding of the process generating the unknown information (Davis and Johnson 1987, p. 197). Decision making

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under risk occurs when we do not know precise data values, but we have a relatively good understanding of what might happen; we know the possible future conditions and the probability that each condition will occur. An example of a situation where risk occurs is the future growth and development of a forest. Statistical models predict not only growth, but also allow calculation of the probability distribution around the expected growth. Furthermore, we can estimate the chance of catastrophic events, such as insect or disease outbreaks and fire, based on historical records. Although some of the estimates are not very precise, we at least understand the process generating these data.

Alternatively, decision making under uncertainty involves the worst-case scenario where we do not even know the possible outcomes, much less have any ability to estimate the probabilities of the outcomes. This situation makes planning difficult, and is particularly common where policy decisions occur within a political process. The FS never knows what species will create the next crisis, and even conservative practices, such as old-growth retention, may leave the organization in an untenable situation if the species of interest requires early or intermediate successional stages.

A modeling anomaly first identified by McQuillian (1986) and termed the declining even flow effect (DEFE) was addressed in an earlier study (Pickens *et al.* 1990). The DEFE is the paradoxical result that subsequent planning iterations using a harvest scheduling model and nondeclining yield constraints can and frequently will select first cutting period harvests lower than the level selected in the first cutting period of the previous planning iteration. The conclusion of the Pickens *et al.* (1990) study was that the DEFE would be dramatically reduced by requirements of the FS to assure spatial and temporal separation of harvesting activities and the existence of previous regeneration harvests on some of the land base.

The same spatial and temporal dispersion constraints have frequently been attacked by forest industry and academicians because of their high opportunity cost, which results because harvest costs are higher per unit on small areas and because highly profitable stands are retained longer, rather than being harvested and replaced with young, vigorous stands soon. Sensitivity analysis conducted as part of the Kootenai National Forest plan showed a 45 percent reduction in present net value (PNV) between an unconstrained profit maximization and the model including the various planning requirements (Pickens *et al.* 1990).

These planning requirements are included for a variety of reasons such as endangered species, community dependence, soil and water protection, and multiple-use concerns. However, arguably the most important rationale for the planning requirements is their tendency to reduce the risk associated with management of forested ecosystems. The risk-reducing nature of the requirements can be divided into two categories:

1. Reduction in the physical and biological risk associated with a diverse landscape.

2. Reduction in production level risk, and therefore enhanced predictability of output levels, because of portfolio diversification.

Risk reduction associated with heading 1 is well understood. Forests with age and species diversity, even when each stand is an even-aged monoculture, tend to not allow insects, disease, or fire to spread as widely as homogeneous forests. However, the risk reduction associated with heading 2 has not previously been identified or evaluated, and is the primary focus of this paper.

The State-of-the-Art for Incorporating Risk into Harvest Scheduling Models

Decision making under risk is relatively well understood, although the analytic tools employed are frequently conceptually complex and difficult to apply. Forestry land allocation models are quite unique because of their large size and the fact that nearly all of the technical information is not known with certainty (Pickens *et al.* 1991). Many recent publications within the forestry literature have addressed special cases, particularly the situation where the production information (e.g., timber yield) is not known with certainty. Early efforts focused on characteristics of solutions where yield information is uncertain (Hof *et al.* 1988, Pickens and Dress 1988, Pickens and Hof 1988), while later efforts emphasize using chance constraints, which assure that a constraint or group of constraints will be satisfied some specified proportion of the time (Pickens *et al.* 1991, Hof *et al.* 1992). Most recent efforts have addressed improved nonlinear programming algorithms (Weintraub and Vera 1991), pragmatic approaches to address practical problems (Hof *et al.* 1995), and spatial covariance relationships (Hof *et al.* 1996). The pragmatic approaches advances are particularly important because they allow calculation of variability around expected production levels and develop formulations which reduce variability without requiring nonlinear or integer programming, or cumbersome iterative approaches, all of which are technically not possible or are operationally very difficult for characteristic large harvest scheduling models.

The Value of Diversification in Reducing Risk

It has long been recognized in the classic finance literature that spreading investments across a range of options can dramatically reduce investment risk so long as covariances between components are small relative to variances (Markowitz 1959).

The risk reduction from diversification occurs because a diversified portfolio can compensate for large losses in one investment by lower losses or gains in other components of the portfolio. The variance associated with any portfolio is:

$$(1) \quad \sigma^2 = \sum_{j=1}^{N}\sum_{k=1}^{N} x_j x_k \sigma^2_{jk}$$

where σ^2 is the variance of return on the portfolio χ_j and χ_k are the level of investment in the jth and kth options, and σ^2_{jk} is the covariance between the jth and kth investments. If j equals k, then σ^2_{jk} is simply the variance of that investment.

The following example demonstrates some of the implications of risk reduction using portfolio diversification. Consider an investor who has $4,000 to invest and four possible investments, each of which has an expected annual return of 10 percent and a standard deviation of 0.1 for each dollar invested. Further, assume that the return is statistically normally distributed. Initially, we will assume that the returns on the various investments are statistically independent.

If the investor chooses to put all $4,000 into investment one, the resulting variance can be calculated by equation 1.

Since all of the χ_i are zero except χ_1, which is $4,000, this simplifies to:

$$\sigma^2 = x_1^2 \sigma_{11}^2 = 4000^2 x.\, 1^2 = 160,000$$

and

$$\sigma = 400$$

If our investor decided to diversity his portfolio equally by putting $1,000 into each of the four investments, the variance of his investment would be:

$$\sigma^2 = 4x\, 1000^2 x.\, 1^2 = 40,000$$

and

$$\sigma = 200$$

Our investor has been able to reduce his risk from a standard deviation of 400 to a standard deviation of 200 by diversifying his portfolio. Furthermore, the expected return remains unchanged at 10 percent, or $400 over a 1-year period. In fact, the expected return is identical for all of the investment situations discussed in this section.

Another way to view the level of risk associated with a management option is to calculate the probability that some critical threshold is not reached. The first step in this process is to calculate the number of standard deviations that the threshold is from the mean. Because we have assumed return is normally distributed, this value is also a "Z-score" from introductory statistics.

The following example uses the critical threshold of zero return, which coincides with the investor not losing on the investment. For the undiversified investor, the *Z* score for zero return is:

$$Z = \frac{x - u}{\sigma} = \frac{0 - 400}{400} = -1.0$$

From a normal probability distribution table, the chance that $Z \geq -1.0$ is 0.8413. Therefore, the undiversified investor will make money in about 84 percent of the years, and will loose money during 16 percent of the years. For the diversified investor, the Z-score for zero return is:

$$Z = \frac{x - u}{\sigma} = \frac{0 - 400}{200} = -2.0$$

The chance that $Z \leq -2.0$ is 0.9772. Therefore, the diversified investor will make money in about 98 percent of the years, and lose money in only 2 percent of the years.

The Importance of Correlation Between Investments in Portfolio Management

Recall that we assumed that the return on the various investments were statistically independent. This assumption is not generally true for either financial investments or forest management decisions. Most financial markets are positively correlated with each other, with some correlations quite strong.

Stocks within the same industry generally move as a group. If one oil company has a good year, it is very likely that other oil companies will also prosper. This translates statistically into strong positive correlations. Furthermore, most other investment alternatives are positively correlated. Generally, the entire stock market either gains or looses together, and the stock and bond markets also tend to move in the same direction. However, the degree of correlation across the entire market is much weaker than within a given industry.

The presence of positive correlations between investments tends to reduce the amount of risk reduction possible from portfolio diversification. If we consider the above example with even diversification among the four possible investments, but with a 0.5 correlation coefficient between each pair of investments, the resulting standard deviation would be 265. This result is between the diversified portfolio value of 200 when independence is assumed and the undiversified portfolio value of 400. If the various investments were all perfectly correlated with each other, then there would be a standard deviation of 400 and a loss of all of the risk reduction potential of diversification.

It is possible that some investments would tend to move in opposite directions. This translates statistically into a situation with negative correlation coefficients. When alternative investments are negatively correlated, it is possible to reduce the variability of return even more than when returns are statistically independent. If the investment was again split evenly between the four investments, and each of the pairs of investments had a correlation coefficient of -0.5, the resulting standard deviation of the investment would be 100. This is only one-fourth of the variability of the undiversified investment, and only half the variability of the diversified portfolio with statistically independent investments. Unfortunately, there are very few investment options that are negatively correlated with overall stock market performance that offer competitive expected returns. Finally, if we could separate the investments into two groups that were perfectly and negatively correlated, then we could eliminate all investment risk and receive an assured 10 percent annual return.

Potential for Using Portfolio Diversification to Reduce Harvest Level Risk

The above examples show the potential to reduce risk by portfolio diversification in financial markets, and emphasize the importance of correlations between the yield of the various options. The diversification strategies can also be applied to the management of a forest to reduce various forms of risk. One important source of risk is the variability associated with timber harvest when forest plans are implemented and growth and yield information is random; this issue is addressed below using the general context of FS planning. Specifically, the implications of forest planning regulations and the current age-class structure of the forest are addressed. Information concerning spatial and temporal correlations of timber yields is limited, and will be addressed below.

The pragmatic approaches work of Hof *et al.* (1995) emphasizes the importance of a portfolio diversification approach to reduce the risk associated with planned timber harvest levels. Their case study demonstrates the value of diversification in the time-dynamic harvest scheduling case when correlations are zero both over time and across the landscape. Furthermore, a significant opportunity to reduce risk has been demonstrated by Hof *et al.* (1996) when positive spatial correlations are included. Their results reduced production level risk by spreading harvest widely across the landscape for a range of alternative harvest targets and harvest cost scenarios.

The current state-of-the-art does not allow inclusion of temporally correlated yield in optimization models because this case generally involves correlation between rather than within rows (Miller and Wagner 1965, Hof *et al.* 1992). Unfortunately, the strongest case can be made for yield correlations over time and within a stand rather than across the landscape at a point in time. The yield at a future point in time is clearly strongly correlated with the current stocking in the stand for two reasons; much of the future stocking will be the same volume that currently occupies the stand and the amount of mortality and new growth is strongly related to the current stocking.

The support for spatially correlated yields is much less compelling. Reed and Burkhart (1985) present and discuss statistical tests for identifying spatial correlations and test a range of parameters for spatial correlation at the stand level. Although some significant spatial correlations are identified, it seems likely that these correlations take place at a very fine scale because they noted that separate plots within a stand often have very different spatial correlation patterns. Furthermore, differences in product classes (their parameter closest to stand yield) generally occurred because of species composition differences. Species composition differences occur in response to microsite differences within the stand.

Czaplewski *et al.* (1994) investigated spatial autocorrelation of diameter growth across widely separated areas in the state of Georgia using continuous forest inventory plots. Their results identified several cases of significant spatial autocorrelation. However, their analysis to identify the specific source of the spatial autocorrelation showed that a large share of the effect resulted from a small area with highly correlated observations, rather than a general trend across the landscape.

Taken together, the results of Reed and Burkhart (1985) and Czaplewski *et al.* (1994) generally support the existence of some degree of spatial autocorrelation in timber yield. However, this relationship is probably not particularly large and the scale where the effect could be expected is uncertain.

CASE STUDY

This study evaluated the change in risk, as measured by the standard deviation, that could be expected as various forest planning requirements were included in the harvest scheduling model. The point of departure for the study is the previous DEFE study (Pickens *et al.* 1990), which evaluated three characteristics of the forest planning process. Each characteristic is present in all forest planning models, but was absent in McQuillian's (1986) evaluation:

1. Spatial and temporal dispersion constraints to assure the 40 acre clearcut size limitation.

2. Prescriptions which allow intermediate harvests and inclusion of more realistic yield information. (Note: McQuillan assumed constant old-growth yield, with regenerated stand yields of zero until age 70. At age 70, yield jumped to 25 mbf per acre, with no further growth thereafter.)

3. Inclusion of a land base which is not entirely old growth.

Characteristics 1 and 3 were evaluated for their impact on production level risk. The second characteristic was not addressed because the impact of more complex yield functions is ambiguous, and depends on the specific yields. However, it is likely that more realistic yield functions would tend to diversify the harvest in any cutting period across more analysis areas because of the inclusion of partial harvests, which were not allowed in McQuillan (1986).

Models including characteristics 1 and 3 were compared with the base model from Pickens *et al.* (1990). This formulation used the resource situation described by McQuillan (1986), but is formulated and solved using the FORPLAN (Johnson *et al.* 1986) harvest scheduling system. The base model includes five analysis areas, each with 1,000 acres and having identical site productivity and stocking. The prescriptions allowed are clearcutting and minimum level management. The forest is currently comprised of old-growth stands which have 15 thousand board feet (mbf) per acre, and no net volume change is expected. Regenerated stands are expected to have no volume until age 70, at which time the volume is 25 mbf/ac and does not change as the stands age. Current product price is $300/mbf, but is expected to increase by 1.5 percent per year for the next 50 years, after which it will not change. The only difference between analysis areas is the cost associated with timber harvesting. The harvest costs are $170, $290, $410, $530, and $650 per mbf for analysis areas 1 through 5 respectively. These costs are assumed to be the same for both old-growth and regenerated stands. The discount rate is 4 percent, and all revenues and costs are assumed to occur at the midpoint of the cutting period. Land area, nondeclining flow, and a limit of harvest below the long-run sustained yield level were the only constraints included in the base formulation. The objective was to maximize present net value over a 12 cutting period planning horizon, with each planning period 10 years long.

Chosen Land Allocations

Tables 1 to 3 present the selected land allocations for the base solution, the solution with spatial dispersion constraints, and the solution when the initial land base is not entirely old growth, respectively.

Table 1.—*Land allocations for the base model*

Cutting period	Analysis areas				
	1	2	3	4	5
1	667				
2	333	333			
3		667			
4			667		
5			333	333	
6				667	
7					667
8	667				
9	333	333			
10		667			
11			667		
12			333	333	

Table 2.—*Land allocations for the model with spatial and temporal dispersion constraints*

Cutting period	Analysis areas				
	1	2	3	4	5
1	250	155			
2	250	250			
3	250	250	23		
4	250	173	250		
5		173	250	250	
6			250	250	173
7			227	250	195
8	250	155		250	
9	250	250			91
10	250	250	23		250
11	250	173	250		
12		173	250	250	

Table 3.—*Land allocations for the modified land base model*

Cutting period	Analysis areas								
	1	2	3	4	5	R11[a]	R12	R21	R22
1	400								
2	200	200							
3		400							
4			481						
5			519	432					
6				284			200		200
7				284		200		200	
8	400				284				
9	200	200			284				
10		400			284				
11			481		148				
12			591	191					

[a] The analysis areas starting with R are previously harvested areas. The first digit represents the original analysis area number, while the second digit indicates the age in cutting periods at the midpoint of the first cutting period.

Inspection of Table 1 shows that the base model employed an "all or nothing" approach when selecting which analysis areas to harvest in each cutting period. All of the scheduled removals were cut from 667 acres of analysis area 1 in the first cutting period. Second cutting period harvests were achieved by harvesting the remaining 333 acres of analysis area 1 and 333 acres from analysis area 2. This pattern continues, with the scheduled harvests taken entirely from the most profitable analysis area in each cutting period.

The pattern of harvests when spatial dispersion/40 acre clearcut limits was included was very different. These constraints require that not more than one-quarter of the analysis area can be harvested in any one cutting period. The logic behind these constraints is that analysis areas generally occupy large contiguous areas, and that they can only be harvested using a checker board pattern. Only one of each block of four 40-acre squares can be cut in any one cutting period (assuming that the "green-up period" is one cutting period). This spreads the harvest of each analysis area over at least four cutting periods. This pattern automatically leads to reduced production level risk because of increased diversification of the areas harvested in any one cutting period.

The pattern of scheduled harvests using the modified land base presented in table 3 also shows some degree of diversification of periodic harvests. It is worth noting, however, that the diversification seen in this case is primarily a result of the choice of previously harvested areas, which were chosen to conform with the spatial dispersion constraints.

Table 4 presents the expected harvest by cutting period, the standard deviation (SD) associated with the expected harvest, and the coefficient of variation (CV) of the expected harvest for each of the three solutions when no inter-analysis area correlation of harvest estimate errors is assumed and the CV for each analysis area is 0.30. Coefficient of variation is calculated as the standard deviation of yield divided by the expected yield, and is a useful method to compare variability when the estimated parameters (cutting period expected means) are quite different.

The average CVs are 0.27, 0.19, and 0.23 for the base, spatial dispersion, and modified land base formulations, respectively. The spatial dispersion constraints produced solutions which were, on average, only 70 percent as variable as the base case solutions. This demonstrates that the variability of projected harvests will, in general, tend to be reduced significantly by inclusion of spatial dispersion constraints. The modified land base solution produced solutions which were 85 percent as variable as the base case solutions.

DISCUSSION

Forest Service land management plans were developed using FORPLAN models which were very highly constrained. Although each forest, and therefore each model, operates under different conditions and constraints, there are certain constraint sets and initial conditions which all forests share. One limitation which is always included is a set of constraints to assure spatial and temporal separation of regeneration harvests. These constraints are often formulated to assure that not more than 25 percent of an analysis area is regenerated within

Table 4.—*Comparison of variability associated with the different model formulations*

Cutting period	Base model formulation			Spatial dispersion formulation			Modified land base formulation		
	Yield[a]	SD	CV	Yield	SD	CV	Yield	SD	CV
1	10,005	3,002	0.30	6,075	1,324	0.22	6,000	1,800	0.30
2	9,990	2,119	0.21	7,500	1,591	0.21	6,000	1,273	0.21
3	10,005	3,002	0.30	7,845	1,594	0.20	6,000	1,800	0.30
4	10,005	3,002	0.30	10,095	1,771	0.18	7,215	2,165	0.30
5	9,990	2,119	0.21	10,095	1,771	0.18	14,265	3,039	0.21
6	10,005	3,002	0.30	10,095	1,771	0.18	14,260	2,477	0.17
7	10,005	3,002	0.30	10,080	1,755	0.17	14,260	2,477	0.17
8	16,675	5,003	0.30	13,875	2,476	0.18	14,260	3,261	0.23
9	16,650	3,532	0.21	13,865	2,683	0.19	14,260	2,477	0.17
10	16,675	5,003	0.30	16,825	2,886	0.17	14,260	3,261	0.23
11	16,675	5,003	0.30	16,825	2,952	0.18	16,285	3,827	0.24
12	16,650	3,532	0.21	16,825	2,952	0.18	19,970	4,201	0.21

[a] Yields are not strictly nondeclining because reported acreages are rounded to the nearest integer.

the time required for harvests to reach "green-up." These constraints also provide an additional benefit because the degree of variability associated with planned harvests is reduced by spreading harvest among many analysis areas.

This "portfolio diversification" reduced the variability of scheduled cutting period harvests by 30 percent in the case study model presented above. However, because of the small number of analysis areas present in the case study, the expected reduction in variability would be higher for actual forest planning models. If the green-up period is one 10-year cutting period, then the maximum reduction in variability would be 50 percent. If the green-up period was greater than one decade, then the degree of portfolio diversification would be even greater because the harvest of a single analysis area would be spread over more than four cutting periods, and the number of analysis areas cut in any one cutting period would be greater. If the yields were positively correlated across analysis areas, then the degree of variability reduction would be less, while negative correlations would provide for even greater reduction in variability.

All national forests have areas which have previously been regeneration harvested. The existence of these previously harvested areas tends to add spatial and temporal diversity to the forest. Furthermore, it tends to smooth the temporal flow of harvest variability. This occurs because the previously regenerated areas add to the diversity of analysis areas harvested. Table 4 shows this tendency for the modified land base formulation. As long as harvests were limited to the old-growth stands, the CV ranged between 0.21 and 0.30. After the regenerated stands became available for harvest in cutting period 6, the CV tended to be smaller with a range from 0.17 to 0.24. Furthermore, since previous harvests have generally occurred over a long period on most national forests, the variability of harvest levels between periods would be expected to be quite low. This would occur because successive cutting periods would have a strong tendency to harvest from the same analysis areas as previous cutting periods.

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ASSESSING CARBON SEQUESTRATION ON PUBLIC TIMBERLAND IN THE CONTERMINOUS UNITED STATES

Linda S. Heath[1]

ABSTRACT.—Carbon was estimated and projected for public timberland using the FORCARB model, linked to a modified version of the Aggregate Timberland Assessment System (ATLAS). Public forests contain about one-third of the carbon in timberland in the conterminous U.S. The average annual carbon flux is greater for public forests than for private forests; however, carbon flux is greater for private forests if carbon in use and energy from harvested wood is considered. Reducing baseline public forest harvests by 25 percent or reducing baseline inventory estimates by 3 percent while holding private forest estimates constant has a relatively small influence on carbon inventory projections.

INTRODUCTION

Increasing concentrations of CO_2 and other greenhouse gases in the atmosphere have prompted the international community to investigate strategies to mitigate emissions. One set of strategies involves sequestering carbon in forests. There have been several studies on carbon sequestration in forests (for example, Heath and Birdsey 1993), including Birdsey and Heath (1995), that reported estimates for public timberlands. None of the studies analyzed and reported carbon for public timberlands in the United States in a way consistent with carbon estimates on private timberland. In this study, I develop a version of FORCARB (Plantinga and Birdsey 1993) to project carbon for public timberland that is available for timber harvest. I project carbon inventory by decade for 50 years, and calculate carbon flux indirectly by subtraction. Both inventory and flux are of interest to policy makers. I also examine disposition and storage of carbon after harvest.

I concentrate on estimating carbon on timberland, which is forest land capable of producing 20 cubic feet per acre per year of industrial wood and is administratively available for timber harvest. About 475 million acres in the conterminous U.S. are considered timberland. Approximately 25 percent of this area is public forest land, of which the USDA Forest Service manages 65 percent. The Rocky Mountain Region has the largest area of public timberland, followed by the North. The Pacific Coast features similar acreage to the North, while the South contains the smallest area (table 1).

Table 1.—*Area*[a] *(thousands of acres) of timberland by region and owner group*

	Owner group		
Region	**National Forest**	**Other Govt.**	**Private Owner**
North	9,545	22,725	125,529
Pacific Coast	23,380	5,696	24,976
Rocky Mt.	35,459	5,986	21,183
South	11,554	9,065	178,690

[a] For National Forest and Private Owner, see Powell *et al.* (1993). Other Government includes Native American lands, from Waddell *et al.* (1989).

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METHODS

Models

The carbon budget model FORCARB has been used to project carbon on private timberland. The model uses forest inventory projections from the Timber Assessment Market Model (Haynes *et al.* 1995) and the Aggregate Timberland Assessment System (ATLAS) (Mills and Kincaid 1992) as a basis for tree carbon and areal extent of forest types. FORCARB estimates carbon in soil, forest floor, and understory vegetation for the forests as partitioned by the ATLAS model in terms of area, forest type, and age-class. The fate of harvested carbon is estimated using a model based on the work of Row and Phelps (1991). There are four disposition categories: products, landfills, energy, and emissions. Emissions include wood burned without generation of usable energy, or emissions from decomposing wood. For more information about FORCARB, see Plantinga and Birdsey (1993) or Heath and Birdsey (1993).

To develop a version for public forest land, I assumed carbon estimates for tree growth, soil carbon, and detrital carbon on public forest land for a specific region, forest type, and age-class to be equivalent to estimates as described in FORCARB for private forest land of average to low productivity. I supposed that most areas are managed passively until harvest, except for certain regions such as the South, where management activities are a common practice. I also assumed that the ratio of carbon in products processed or manufactured from harvested timber from public forests is equal to the ratio for harvests from private forests.

Data

Forest inventory data for public forests was extracted from two sources. In the Eastern U.S., data were compiled from the USDA Forest Service Forest Inventory and Analysis Eastwide database (Hansen *et al.* 1992). In the Western U.S., data were compiled from the USDA Forest Service RPA database (Powell *et al.* 1993).[2] The majority of the data in the Eastwide data base was collected recently using similar sampling designs. Much of the data for the West from the RPA data base has not been updated since the 1987 compilation of data, with the exception of most of the Southern Rocky Mountain States.

Data was compiled for two owner groups, National Forest and Other Government. Data for National Forests in the West were collected using a different sampling design, and it is not known how that design may affect sample estimates (compared with the inventories collected on private lands). Currently, new inventories are being undertaken on western National Forest lands using protocols comparable to private forest land inventories. Other Government data include all non-National Forest Government owners, including other Federal, State, county, and municipal owners. Native American lands are also included here because they have been traditionally considered public land, and including them in this analysis was necessary for consistent results. Most of the Other Government data were collected using sampling designs similar to those used on private lands.

Area and average volume were compiled by region, ownership (National Forest or Other Government), major forest type, and age-class. Forests of unknown age or considered uneven aged were assigned to an age-class based on their volume and stocking. Areas with age-class zero sometimes lacked data on forest type. Those areas were assigned forest type based on the estimated percentages of forest type in the county.

Scenarios

For the base scenario, I used removals for National Forest and Other Government from the base run[3] for the 1993 RPA Timber Assessment (Haynes *et al.* 1995). I compiled the estimates by decade for the period 1980–2040. The projection was started in the year 1980 for regions with older inventory data, and in the year 1990 for regions with more recent inventory data. The base scenario is not the most likely scenario; it is simply the scenario that would occur if the model is accurate, and current policy remains unchanged.

I ran two other scenarios to investigate the sensitivity of the results to changes in inputs. The second scenario was the same as the base, except that I reduced harvests by 25 percent. In the third scenario, I reduced the initial inventory by 3 percent, while keeping harvests the same as the base. Estimates from privately-owned forests were held constant. I chose 3 percent because the sampling error for total volumes for States is often on the order of 3 percent.

RESULTS AND DISCUSSION

Carbon inventories for three scenarios on public timberland are shown in figure 1. Public timberland sequestered more carbon than it emitted. The amount of carbon was similar even if harvests were reduced by 25 percent or if beginning inventory featured 3 percent less volume in all

[2] *Volume and area by age class for Washington and Oregon were provided by Dr. Andrew Plantinga, currently with the University of Maine, Orono, ME.*

[3] *Log Run 207. Dr. Richard Haynes, PNW Research Station, Portland, OR, provided these estimates.*

forest types, indicating that small differences in harvests and inventory may have a relatively small effect on results.

Table 2 lists carbon flux over time for public timberland and carbon in use from removals from public timberland, along with carbon flux from privately owned U.S. timberland for comparison.

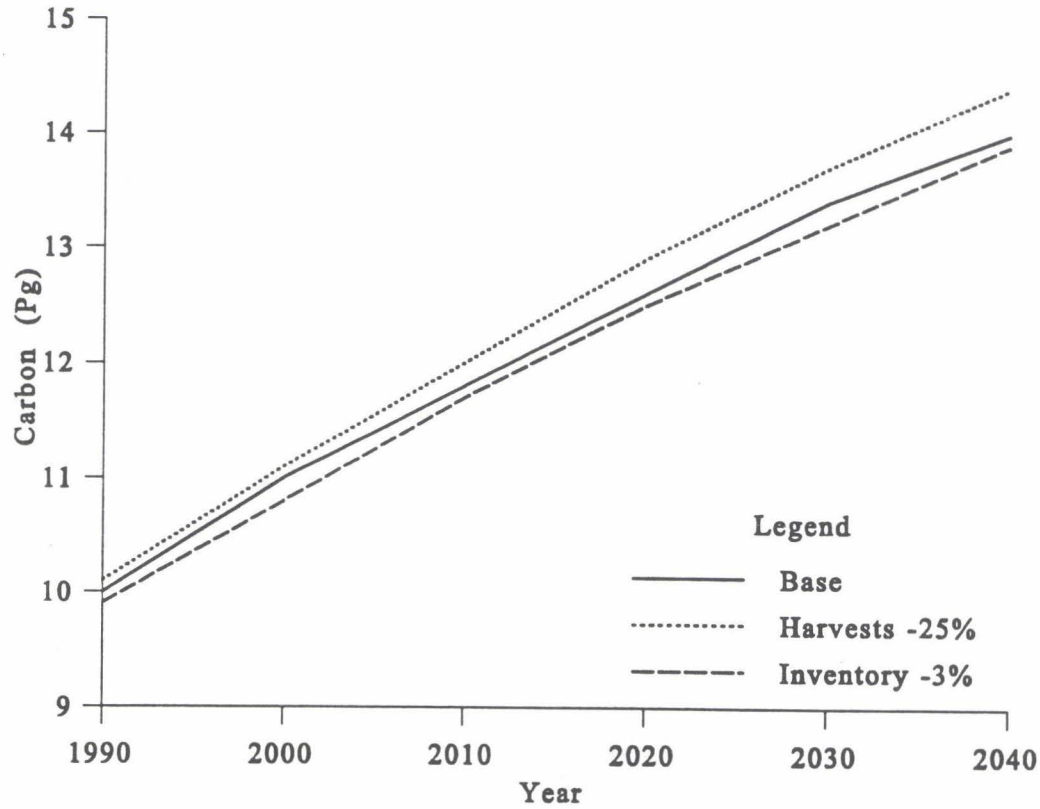

Figure 1.—*Carbon inventory for three scenarios for public timberland and products.*

Table 2.—*Carbon flux[a] (Tg/yr) for timberland and in use and energy[b] for base scenario[c]*

Period	Owner group			
	Private		Public	
	Forest	In use	Forest	In use
1990–1999	76	—	82	—
2000–2009	58	129	76	15
2010–2019	32	134	72	15
2020–2029	13	139	65	15
2030–2039	2	150	58	15

[a] A positive flux indicates that the amount of carbon in forests in increasing. Tg/yr = teragrams per year

[b] Includes carbon in products, landfills, and emitted for usable energy.

[c] Scenario 207 (Haynes *et al.* 1995). I obtain removals from public timberland from this scenario.

Previously, Birdsey and Heath (1995) indicated that carbon was accruing on U.S. timberlands on both National Forest and Other Government lands. Using simple inventory and growth relationships, they projected an average increase of 83 teragrams per year (Tg/yr) on National Forests, and 49 Tg/yr on Other Government between the years 2000 and 2040. Our analysis indicates there is an increase, but that it is about half that amount. Part of the difference may be because their estimates include Alaska timberlands, but the size of acreage in Alaskan timberland is at most 5 percent of either type of public ownership, and it is doubtful such a small land base could sequester enough carbon to make up the difference in estimates.

Carbon is accumulating in public timberland at a greater rate than in private timberland. However, when carbon in use and energy from timber removals is also counted, more carbon is being sequestered in private timberland. The actual accounting system is thus very important in determining whether an activity in forests is sequestering more carbon or less carbon than another activity.

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MODELING THE ATMOSPHERIC DYNAMICS WITHIN AND ABOVE VEGETATION LAYERS

W.E. Heilman and J.C. Zasada[1]

ABSTRACT.—A critical component of any silvicultural treatment is the creation of suitable microclimatic conditions for desired plant and animal species. One of the most useful tools for examining the microclimatic implications of different vegetation treatments is the use of atmospheric boundary-layer models that can simulate resulting micrometeorological conditions within and above vegetation layers. A two-dimensional atmospheric boundary-layer model has been successful in simulating the atmospheric environments within and above forest vegetation layers that have undergone different types of silvicultural treatments. Model simulations in conjunction with current observations reaffirm the importance of forest overstory vegetation in affecting the dynamic and thermodynamic properties of the atmosphere near the surface.

INTRODUCTION

Natural and human-caused disturbances are an integral part of ecosystem dynamics in the upper Great Lakes region. The scales at which disturbances occur vary from the level of seedlings to the landscape level. The responses of plant species to changing conditions brought on by natural and human-caused disturbances may be positive or negative depending on growth requirements for the individual plant species and the nature of the disturbances. Responses to disturbances will ultimately produce changes in primary productivity, abundance, structure, and composition of plant species.

Altered microclimate conditions resulting from natural and human-caused disturbances that add, remove, or modify existing vegetation may be more favorable for some plant species while increasing environmental stress for others. The vegetation characteristics and patterns that result from these disturbances in turn can further modify the near-surface dynamic and thermodynamic properties of the atmosphere. For example, early growing-season frost episodes in vegetation-managed areas of the upper Great Lakes region depend to a large degree on the types of vegetation management treatments that have been applied. Frost episodes are particularly important in red oak (*Quercus rubra*) regeneration in the upper Great Lakes region (McGee 1975, Crow 1992) because they can damage young red oak and associated species during bud break in the spring. Management treatments that specifically alter forest overstory conditions may be especially important in influencing the frequency and severity of early growing-season frost episodes.

A full understanding of the implications of forest management practices on forest microclimates requires an assessment of the relevant dynamic atmosphere-forest interactions that occur in managed areas. This study focuses on the dynamic behavior of the atmospheric boundary layer in response to different intensities of forest overstory cutting through both observations and numerical model simulations. An atmospheric boundary-layer research model that utilizes appropriate vegetation and turbulence parameterizations was used to examine how different forest overstory densities impact the dynamic turbulent and non-turbulent behavior within and above forest vegetation layers, and to provide more in-depth atmospheric information than what is possible from limited instrument measurements alone. Emphasis was placed on examining the dynamics of a specific frost episode and the evolution of the nocturnal boundary layer under different soil-moisture conditions at a study site on the Chequamegon National Forest near Park Falls, WI.

MODEL DESCRIPTION

Simulating the small-scale atmospheric dynamics within and above vegetation layers requires an atmospheric model that can resolve critical atmospheric-vegetation interactions, including both atmospheric turbulent and non-turbulent effects. Atmospheric models of this type are referred to as boundary-layer models. For this study,

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the two-dimensional boundary-layer model developed by Heilman and Takle (1991) is used; it incorporates vegetation parameterizations from the one-dimensional boundary-layer model developed by Heilman (1984). Previous applications of the model include simulations of nocturnal turbulence characteristics associated with small-scale drainage flows over sloping terrain (Heilman and Takle 1991) and the simulation of daytime upslope flows in response to surface heating (Heilman 1988).

Atmospheric Mean Variables

The non-turbulent atmospheric variables predicted by the level-3 model include horizontal and vertical wind components, temperature, specific humidity, and dew. The horizontal wind components are simulated by solving prognostic equations that account for wind-speed changes due to advection, changes in the atmospheric pressure gradients (including temperature effects), the Coriolis effect, vertical fluxes of momentum, and drag effects due to the presence of canopy elements. The vertical wind component is computed from the incompressible form of the atmospheric continuity equation. Temperature is predicted with a prognostic equation that includes advection effects, diffusion effects, and heating and cooling effects due to the flux of heat between vegetation elements and the air and between the ground and the air. Similarly, the specific humidity is predicted with a prognostic equation that accounts for advection and diffusion effects, as well as the transfer of moisture between vegetation elements and the air, and between the ground and the air. Nocturnal dew formation on vegetation is predicted with a prognostic equation that includes precipitation, transpiration, and evaporation effects.

Atmospheric Turbulence Variables

The turbulence portion of the level-3 model consists of four prognostic equations that are used to define the temporal evolution of turbulence in the atmospheric boundary layer. Turbulent kinetic energy (TKE), defined as the sum of the variances of the horizontal and vertical wind speed components, is predicted with a prognostic equation that includes the effects of advection, diffusion, buoyancy production or dissipation, production of turbulence due to airflow around canopy elements, and non-buoyant dissipation of turbulence. The non-buoyant dissipation of turbulence in the atmosphere is dependent on the characteristic sizes of turbulent eddies, with dissipation being much more prevalent at small eddy sizes. A prognostic equation for the characteristic length-scale of turbulent eddies at a particular location is included in the model. It takes into account the effects of advection, diffusion, enhancement of eddy sizes due to vertical wind shears, and the natural breakdown of turbulent eddies once they have formed. Finally, parameterizations of the numerous diffusion coefficients used in the model include both temperature variances and temperature/specific humidity covariances. In order to close the set of model equations, temperature variance and temperature/specific humidity covariance prognostic equations are included. Diagnostic equations are incorporated for simulating all other turbulent quantities, including the horizontal and vertical TKE components, and the horizontal and vertical turbulent fluxes of momentum, heat, and moisture. Within the numerous prognostic and diagnostic equations for the atmospheric turbulence variables are parameterizations that account for vegetation effects on turbulence generation.

Radiation and Soil Parameterizations

Radiation processes play an important role in the diurnal evolution of the atmospheric boundary layer. Upward and downward fluxes of longwave and shortwave radiation at the ground and at the top of vegetation layers contribute to the heating and cooling of the boundary layer. The force-restore method of Deardorff (1978) is applied in the model to calculate surface temperatures. This method calculates an energy balance at the ground based on longwave radiation flux contributions from vegetation, the ground, and atmospheric moisture, and on the solar shortwave radiation flux. Surface temperatures are predicted using net radiation, sensible heat flux, and latent heat flux values at the ground surface, along with deep-soil temperatures. The accurate predictive capabilities and relative simplicity of the force-restore method make it an attractive method for surface temperature prediction. Because soil moisture affects the energy balance at the surface through latent heat fluxes and altered radiation fluxes, the force-restore method also includes a prognostic equation for the soil volumetric moisture concentration. This equation includes evaporation, transpiration, precipitation, and deep-soil moisture effects.

STUDY SITE DESCRIPTION

In 1987, the USDA Forest Service, North Central Research Station in Rhinelander, WI and the Chequamegon, Nicolet, and Ottawa National Forests developed an Oak Administrative Study (OAS) to focus on improving the quality of northern red oak seedlings in nurseries and on monitoring the growth of red oak seedlings on selected research sites in northern Wisconsin. One particular research site established as part of the OAS was the Willow Springs Oak Regeneration Study site on the Park Falls District of the Chequamegon National Forest in May, 1989. This study site is situated on an 80 acre mixed hardwood region (Acer-Viola/Osmorhiza vegetative habitat type) with sandy loam soil that is moderately drained. The terrain is generally flat (0-5 percent slope). The study site was divided into four 20-acre plots. One plot was thinned to 75 percent of the

original crown cover (canopy area index (CAI) = 3.9) and another plot was thinned to 50 percent of the original crown cover (CAI = 2.1). A third plot was clearcut (CAI = 0.0) while the final plot was left untouched to act as a control (CAI = 5.7). Overstory tree heights are approximately 20 m. The understory vegetation was treated in the logged plots using various combinations of disking and spraying with a herbicide. Following the understory treatments, 1-year-old bare-root and containerized red oak seedlings and pre-germinated acorns were planted in all the study plots in May, 1989. Since the time of seedling and acorn planting, the growth and survival of the red oak seedlings and other understory vegetation has been and continues to be monitored.

In order to better understand the impacts of the different silvicultural treatments on the micrometeorological environments within the study plots, a micrometeorological monitoring network was set up on three of the four study plots in 1994. A 10-m tower was installed and instrumented in the control, 50 percent overstory-reduced, and clearcut plots. Instruments were placed on the towers at heights of 2.5 m and 10 m to measure air temperature, relative humidity, wind speed, and wind direction. Thermocouples were mounted on stakes at three locations near each tower at heights of 2 m, 1 m, 0.5 m, and 0.25 m to obtain characteristic profiles of near-surface temperatures. Thermocouples were also placed at depths of 0.05 m, 0.1 m, 0.2 m, 0.5 m, and 1 m at the stake locations to obtain characteristic soil-temperature profiles. Photosynthetically active radiation (PAR) and net radiation sensors were placed near each tower to determine the radiation characteristics within the study plots. Scan times for the different sensors ranged from 10 seconds to 10 minutes, and average conditions were reported hourly to data loggers in each study plot. Micrometeorological data from the sensors have been collected every day from 1 January 1994 to the present, with a few minor data gaps.

OBSERVATIONS AND SIMULATION RESULTS

The presence of overstory vegetation layers influences the atmospheric environments within and above these layers during both daytime and nocturnal periods. During the daytime, overstory vegetation layers reduce the amount of solar radiation reaching the surface, and alter the radiation and energy balances at the surface. The daytime evolution of surface temperatures depends to a large extent on these radiation and energy balances. The daytime heating of the atmospheric boundary layer, in turn, depends to a large extent on the upward flux of heat from the surface when surface temperatures exceed lower atmospheric temperatures. Vegetation elements also act as a source of moisture for the atmospheric boundary layer through transpiration processes. Moisture in the atmospheric boundary layer influences the longwave radiation fluxes and the evolution of both daytime and nocturnal temperatures. Examples of the effects of different overstory vegetation densities on nocturnal near-surface temperatures as measured at the Willow Springs study site are shown in figure 1. From about Day 150 (30 May 1994) till Day 290 (17 October 1994) when leaf-area densities in the overstory vegetation were significant, large nocturnal temperature differences were observed between the 50 percent overstory-reduced plot and the clearcut plot, and between the control plot and clearcut plot. Temperature difference maxima reached 5 °C for the 50 percent overstory-reduced plot vs. the clearcut plot, and exceeded 6 °C for the control plot vs. the clearcut plot on three occasions. The higher nocturnal

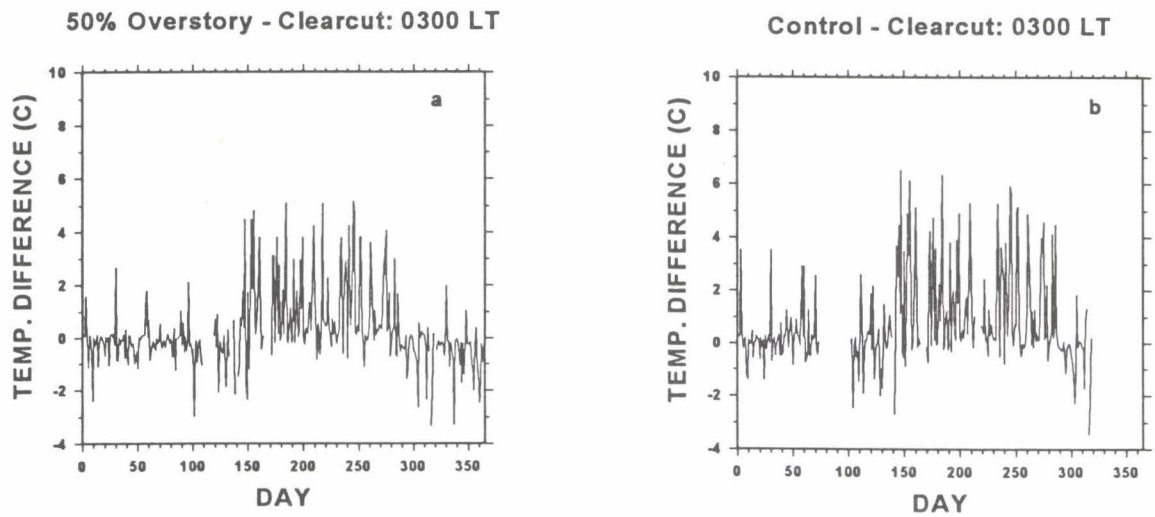

Figure 1.—*Temperature differences in 1994 at 0300 LT between (a) the 50 percent overstory-reduced plot and the clearcut plot, and between (b) the control plot and the clearcut plot at 0.5 m above the surface at the Willow Springs study site.*

temperatures observed in the 50 percent overstory-reduced and control plots on numerous nights during the Day 150-290 period are due to the increased downward flux of longwave radiation resulting from the overstory vegetation, the increased downward flux of longwave radiation resulting from enhanced atmospheric moisture contents within the vegetation layers, and from the thermal inertia provided by the overstory vegetation (Potter 1999). Observed temperature differences increased from the 2.5 m level to the 0.5 m level. The night-to-night fluctuations in temperature differences can be attributed to wind-speed changes and cloud-cover conditions over the Willow Springs study site. Temperature differences are reduced as wind speeds increase because the increased atmospheric turbulence due to horizontal and vertical wind shears acts to minimize any spatial gradients of temperature and moisture. The presence of periodic cloud cover and increased low-level moisture also reduces the amount of cooling at the surface through enhanced downward fluxes of longwave radiation over the entire study site.

Afternoon (1500 LT) temperature differences tended to be slightly larger in magnitude, with temperatures approaching 8 °C cooler on several occasions in the control plot as compared to the clearcut plot at a height of 0.5 m during the same period from Day 150-290. As with the nocturnal temperature differences, large day-to-day fluctuations were observed and can be attributed mainly to wind speed and cloud cover/low-level moisture variations.

Overstory vegetation also has a major impact on the vertical profiles of temperature within the vegetation layers, particularly at night when turbulent mixing due to wind shear is usually less than during the daytime. During calm and cloud-free conditions at night, surface temperatures decrease rapidly after sunset due to radiational cooling if no overstory vegetation is present. The cooling of the ground produces a nocturnal inversion layer above the surface where temperatures increase rapidly with height. Atmospheric turbulence within inversion layers is suppressed, thereby diminishing the turbulent transport of warmer air from higher levels downward to the surface. This reduced atmospheric mixing further enhances the cooling of the surface. If overstory vegetation is present, the inversion layers that develop within the vegetation layers in the late afternoon or early evening are much weaker than the inversion layers that exist in clearcut areas. Figure 2 shows the observed near-surface vertical temperature gradients in the Willow Springs clearcut and control plots in 1994. In the clearcut plot (fig. 2a), vertical temperature gradients in the 0.5 - 2.5 m layer above the surface often exceeded 1.2 °C m^{-1} between Day 150 and Day 290. Prior to this period in 1994, larger temperature-gradient magnitudes were observed as a result of snow cover. In the 50 percent overstory-reduced and control plots, near-surface temperature gradients were much less between Day 150 and Day 290, with the control plot having the smallest nocturnal temperature gradients (fig. 2b). The figures clearly show the impact that leaves from the overstory vegetation have on near-surface temperature gradients. A distinct transition occurred near Day 150, corresponding to the full emergence of leaves in the overstory vegetation in the spring. Night-to-night fluctuations in the near-surface temperature gradients due to wind speed variations and cloud cover/low-level moisture conditions were also observed to be much smaller in the 50 percent overstory-reduced and control plots as compared to the clearcut plot from Day 150 until Day 290.

The evolution of nocturnal inversion layers within and above forest overstory layers is an important atmospheric

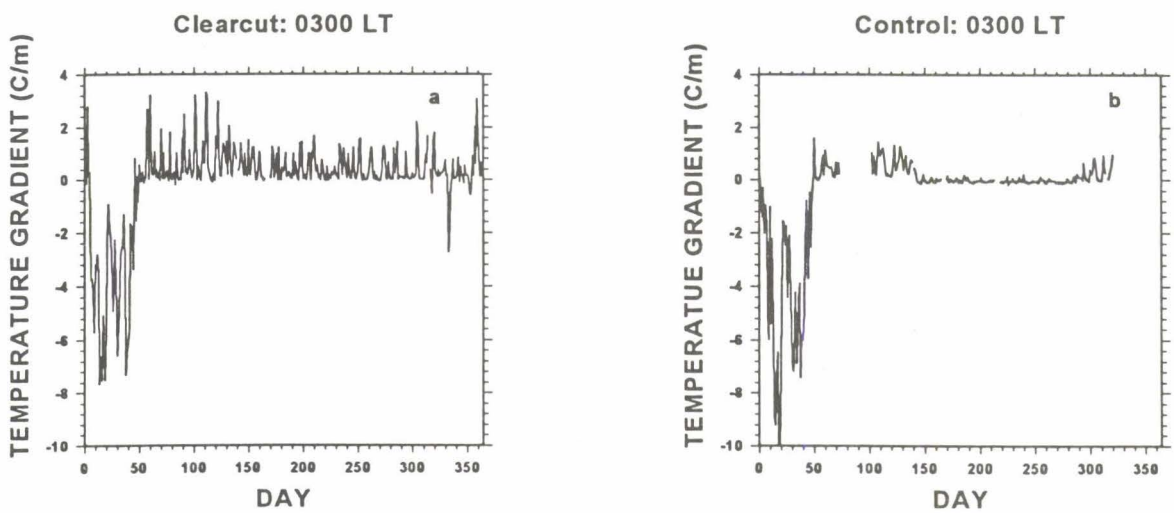

Figure 2.—*Near-surface vertical temperature gradients in 1994 at 0300 LT in (a) the clearcut plot, (b) the 50 percent overstory-reduced plot, and (c) the control plot at the Willow Springs study site.*

dynamic process that results from cooling of the surface and vegetation elements, and is strongly influenced by the overstory vegetation characteristics. A particular disturbance that depends to a large degree on the evolution of the nocturnal inversion layer is frost. Observations and model simulation results are presented for the night of 1-2 June 1994 (Day 152-153) when a significant frost episode under calm conditions occurred in the Willow Springs clearcut plot, but no frost was reported in the 50 percent overstory-reduced or control plots. Figure 3a shows the observed evolution of the near-surface temperatures (0.25 m above the surface) in the control, 50 percent overstory-reduced, and clearcut plots on this particular night. Temperatures in the clearcut plot decreased rapidly after 1800 CDT (Day 152.75) and dropped below 0 °C by 2100 CDT. However, near-surface temperatures in the 50 percent overstory-reduced and control plots decreased less rapidly after 1800 CDT and never dropped below 0 °C that night. Differences in radiational cooling of the surface after sunset in the different overstory treatment plots resulted in maximum temperature differences among the plots during the night. The stable inversion layers that developed over the study plots on this evening acted to suppress the turbulence within them and inhibited any mixing of warmer air from above into the inversion layers. This led to maximum temperature differences among the plots after sunset. After sunrise, the nocturnal inversion layer eroded from below due to surface heating which then increased near-surface turbulent mixing and reduced any temperature differences between the plots. Temperature differences between the plots decreased rapidly after sunrise and remained relatively small throughout the daytime hours of Day 153. The strength of the nocturnal inversion layers within the individual study plots is reflected in the near-surface vertical temperature gradients that developed during the evening and early-morning hours of Day 152-153 (fig. 3b). Large positive near-surface vertical temperature gradients in the clearcut plot during the nighttime hours of Day 152-153 suggest the presence of a strong inversion layer over the clearcut plot resulting from significant surface cooling in the absence of any overstory vegetation. Temperature gradients in the 50 percent overstory-reduced and control plots were much smaller in magnitude, with temperatures at 0.25 m observed to be slightly warmer than the 2 m temperatures in the control plot during the nighttime hours. Diminished surface radiational cooling in the non-clearcut plots resulted in very weak inversion layers underneath the forest overstories. Although this suggests a stronger tendency for more vertical turbulent mixing of heat from above under less stable conditions, turbulence within the vegetation layers was minimal on this night due to very low-wind speeds and enhanced turbulence dissipation associated with the forced small turbulent eddy sizes within the vegetation layers.

Simulated temperature and TKE profiles corresponding to 0200 CDT on 2 June 1994 (Day 153) are shown in figure 4. At that time, the temperature gradient over the lowest 10 m in the clearcut plot was approximately 0.7 °C m^{-1}, in contrast to the 50 percent overstory-reduced and control plots where average temperature gradients were between 0.1 °C m^{-1} and 0.2 °C m^{-1} (fig. 4a). These characteristic temperature profiles were associated with simulated nighttime net radiation flux values (not shown) at the surface that ranged from about -70 W m^2 in the clearcut plot to about -40 W m^2 in the 50 percent overstory-reduced plot and -25 W m^2 in the control plot. These upward fluxes of net radiation were at a maximum

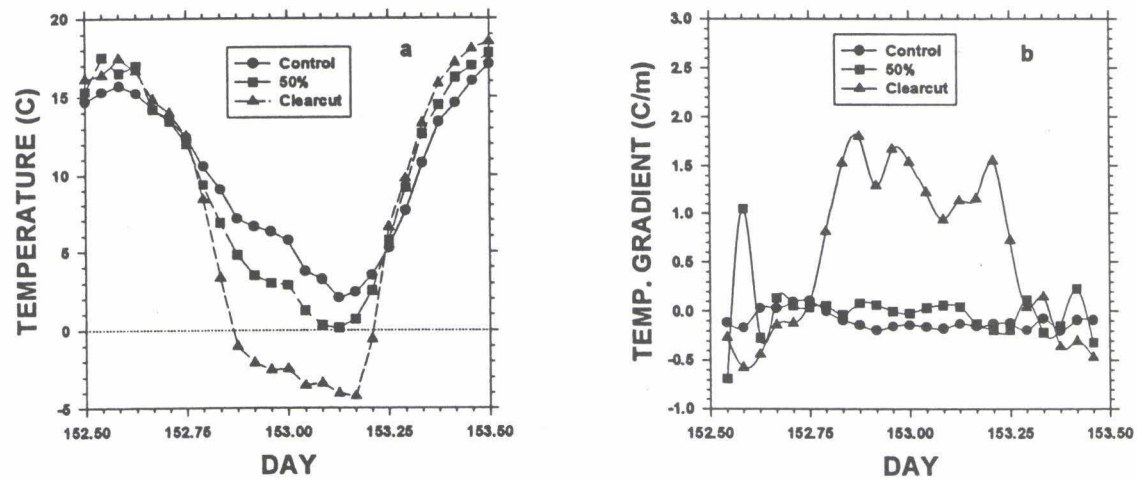

Figure 3.—*Near-surface (0.25 m) temperature evolution (a) and near-surface (2 m - 0.25 m layer) vertical temperature gradient evolution (b) in the control, 50 percent overstory-reduced, and clearcut plots from 1200 CDT on 1 June 1994 (Day 152.5) to 1200 CDT on 2 June 1994 (Day 153.5) at the Willow Springs study site.*

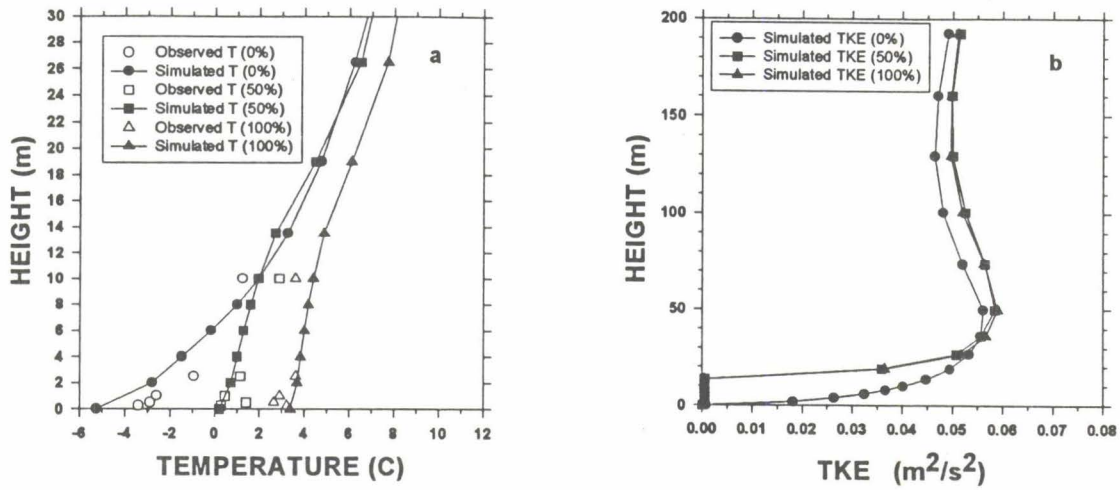

Figure 4.—*Simulated and observed profiles of (a) temperature and simulated profiles of (b) turbulent kinetic energy at 0200 CDT on 2 June 1994 (Day 153) in the clearcut (0 percent), 50 percent overstory-reduced (50 percent), and control (100 percent) plots at the Willow Springs study site.*

shortly after sunset in the simulations over all the treatment plots, and the flux slowly decreased throughout the nighttime hours. However, the decrease in the upward flux of net radiation was more significant in the clearcut plot because surface temperatures decreased more rapidly there, which reduced the upward flux of longwave radiation over time. The model simulations revealed that the presence of forest overstory vegetation in the other plots enhanced the downward flux of longwave radiation and reduced the nocturnal surface net radiation change throughout the night. Larger atmospheric moisture contents within the vegetation layers also contributed to the reduced net upward flux of radiation at the surface during the nighttime hours.

The simulated turbulence structures within the nocturnal inversion layers present over each of the plots are shown in figure 4b. The simulations indicate very low TKE values over each treatment plot compared to typical TKE values during daytime hours. This is a result of the inherent atmospheric stability and large dissipation of turbulence within the inversion layers, along with the lack of any significant turbulence generation from wind shears. Within the vegetation layers in the 50 percent overstory-reduced and control plots, TKE values are further diminished because turbulence dissipation is more significant within the vegetation layers where turbulent eddies are limited in size by the presence of canopy elements and their proximity to the ground. Maximum simulated TKE values appear near 50 m above the surface over all treatment plots.

The impact of overstory density on nocturnal vertical heat-flux profiles was also examined in the model simulations. In the clearcut plot, maximum downward fluxes of sensible heat occurred at the surface, although these fluxes were small compared to typical daytime upward fluxes of heat because of the strong stability within the nocturnal inversion layer above the clearcut plot. In the 50 percent overstory-reduced and control plots, simulated maximum downward fluxes of sensible heat occurred just above the overstory tops. This simulated behavior of heat flux was due in part to the temperature profile behavior in the different plots (see fig. 4a), with the largest lapse rate occurring just above the surface in the clearcut plot. Also contributing to the simulated smaller downward heat fluxes in the plots containing overstory vegetation is the reduced turbulence underneath the overstory vegetation (see fig. 4b).

Surface moisture conditions also influence the atmospheric dynamics associated with nocturnal inversion-layer development and frost occurrence over vegetated surfaces. Soil moisture present at or near the surface reduces the amount of nighttime surface cooling and contributes to the moistening of the atmospheric boundary layer. Model simulations were carried out to examine the sensitivity of nocturnal near-surface temperature profiles and turbulence values to different soil moisture concentrations in the presence of different forest overstory densities. The simulations reveal that nocturnal surface temperatures in clearcut areas are typically 8 °C colder if soil conditions are dry as opposed to saturated, assuming calm and clear conditions prevail. This suggests an increased probability of frost occurrence in clearcut areas with typically dry soil conditions. The presence of overstory vegetation reduces the amount of surface cooling regardless of the soil-moisture contents, but the reduction in surface cooling is more significant when soil-moisture contents are less than 33 percent

saturation. As soils become wetter, the impact of increasing forest overstory densities on nocturnal surface temperatures is minimized. The simulations also reveal that weaker nocturnal inversion layers develop over areas with wetter soil. Weaker inversion layers imply less stability within them and the potential for larger TKE. Model simulations of nocturnal TKE sensitivity to soil-moisture conditions under different forest overstory densities showed that near-surface TKE values tended to be about 15 percent higher in clearcut areas under saturated soil conditions as opposed to dry soil conditions. When overstory vegetation was present, increasing soil moisture had little impact on TKE values within the overstory vegetation layer. However, above the top of the overstory vegetation, TKE values were again about 15 percent larger when the soil was saturated as opposed to dry soil conditions.

CONCLUSIONS

Observations and modeling results from this study indicate that management practices which modify overstory vegetation can alter near-surface microclimatic conditions. In particular, the evolution of nocturnal temperatures and the potential for early growing-season frost episodes are dependent on overstory vegetation densities. Large nocturnal surface temperature differences can arise between clearcut areas and areas with overstory vegetation present. Overstory vegetation contributes to the downward flux of longwave radiation at night and reduces the amount of ground-surface radiative cooling. Nocturnal inversion layers that develop within and above overstory vegetation layers are typically much weaker than the inversion layers that develop over clearcut areas. Atmospheric turbulence and associated turbulent fluxes of heat and moisture within these inversion layers also reflect the presence or absence of any forest overstory vegetation. Soil-moisture variations in clearcut and non-clearcut areas also play a role in modifying the evolution of nocturnal inversion layers. Wet soils tend to increase near-surface nocturnal turbulence values in clearcut areas and above canopy tops in non-clearcut areas. The increased turbulence values are a result of smaller vertical temperature gradients within the nocturnal inversion layers when soils are wet, thereby enhancing the amount of vertical mixing of heat and moisture.

Atmospheric boundary-layer models are useful tools for examining the effects of different forest management practices on forest microclimates. Although boundary-layer models are typically not used operationally, they can provide researchers valuable insight into the dynamic behavior of the atmosphere within and above vegetation layers. Modeling results from this particular study can also be used by forest managers in their development of silvicultural treatments that produce microclimates most suitable for enhancing the regeneration of microclimate-sensitive tree species in the upper Great Lakes region.

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THE IMPACT OF CLIMATE CHANGE ON GLOBAL TIMBER MARKETS

Brent Sohngen, Robert Mendelsohn, and Roger Sedjo[1]

ABSTRACT.—This paper assesses the economic impact of climate change on global timber markets. The results of a large scale ecological model are linked to an optimal control model of global timber markets. The results suggest that climate change may enhance global timber production and reduce prices. The results are driven by several important intertemporal adaptations. First, harvests increase over time as timber growth increases. Second, timberland management in emerging region plantations increases during the transition period to compensate for potential losses in the temperate zone. Third, harvests in some extensive regions increase during the transition to compensate for these losses.

INTRODUCTION

Global climate change is predicted to have broad and far-reaching consequences for ecosystems across the globe (Haxeltine and Prentice 1996, Neilson 1995, Melillo *et al.* 1993). As climate changes, water, nitrogen, and carbon cycles will shift, altering the underlying productivity of land. Climate change is predicted to have two critical effects on forested ecosystems: changes in ecosystem production in existing forests (Melillo *et al.* 1993), and changes in the structure of forested ecosystems (Haxeltine and Prentice 1996, Neilson 1995).

Much of the current ecological modeling has focused on predicting steady state changes in ecosystem distribution and production that result from doubled CO_2 climate change experiments (see, for example, VEMAP Members, 1995). Such steady state predictions suggest that large areas of land currently in forests will shift from one biome to another, including shifts from one forest type to another, and shifts from forest to non-forest. With these results, ecologists have suggested that existing forest lands will be stressed to the point of dieback during climate change, as areas that shift must adapt to new climatic conditions (King and Neilson 1992, Smith and Shugart 1993).

The question of forest adjustment during climate change, however, relies heavily on human adjustment and adaptation. Many forests across the globe are managed intensively for products such as lumber and paper. In particular, some of our most heavily managed forests exist in the temperate zone, where ecological models predict much of the stress will occur. In order to assess both the ecological and economic adjustment to a changing climate, it is critical to link ecological and economic models.

Several authors have considered the link between ecological and economic models in the context of climate change. The seminal piece, Binkley (1988), utilized a global timber market model, but considered only ecological adjustments in the boreal region. A more recent analysis by Perez-Garcia *et al.* (1997) examined the effect of changes in net primary productivity on global timber markets, without considering stock effects, such as a shift in species distribution.

Another analysis, Solomon *et al.* (1996), considered results of two ecological models (BIOME—Prentice *et al.* 1993 and IMAGE 2.0—Alcamo 1994), and economic predictions separately. With increasing human needs due to GDP and population growth, and potentially declining forest stocks, they predicted difficulties in timber market adjustment. Unfortunately, this exercise did not account for human adaptation and adjustment across both time and space during the transition from our current climate to an increased CO_2 climate.

In this paper, we present the results of an ecological-economic modeling effort which captures human adjustment in timber markets to climate change. Because ecological models predict only steady state changes, we begin with a set of steady state results for the BIOME3 model under current and doubled CO_2 climates (Haxeltine and Prentice 1996). These results are then linked with a dynamic model of climate change to develop transient predictions of ecosystem change. Such

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transient predictions are then introduced into a dynamic optimization model of global timber markets. The timber market model captures the human response to these changes, accounting for shifts in ecosystem distribution and production across the globe. The economic model is based on Sedjo and Lyon (1990) and Sohngen and Mendelsohn (1998).

ECOLOGICAL MODELS

The BIOME3 model is used to predict the steady state distribution of ecosystem types and net primary productivity (NPP) for 0.5°x 0.5° grid cells across the globe. Baseline and climate change results of the BIOME3 model are presented in Haxeltine and Prentice (1996) and Haxeltine (1997). This research represents a collaborative effort between the BIOME3 modeling group and the authors. Geographic Information Systems (GIS) techniques are used to compare baseline conditions to doubled CO_2 conditions in order to determine the proportion of each ecosystem type that converts to something else, the relative size of ecosystem types after climate change, and the percentage change in net primary productivity for specific ecosystem types (table 1). The pathway of change (type to type) and separate regional results are also determined, but not shown in table 1. Steady state ecological results used in this paper are based on two doubled CO_2 experiments: the Hamburg T-106 model (from Lennart Bengtsson, Max Planck Institute for Meteorology in Hamburg) and a run provided by Michael Schlesinger (University of Illinois).

Dynamic scenarios of ecological change must be introduced in order to make these steady state results useful for economic analysis. For purposes of this study, climates are assumed to change linearly between now and 2060, as suggested by the Intergovernmental Panel on Climate Change (1996), and then stabilize. Dynamic ecosystem adjustments are assumed to occur proportionally to these linear adjustments in climate. Alternative pathways were considered in Sohngen (1996). Longer term adjustments changed the results only when the most valuable timber types were significantly affected by climate change.

Changes in the area of ecosystem types are predicted to occur along one of two pathways or scenarios. The first scenario involves stock dieback, followed by either natural or managed regeneration, depending on the management class. In terms of table 1, this scenario predicts that the area of land included in the "shifting proportion" column dies back during climate change. Dieback represents a rather dramatic impact of climate change on stocks, but it is one suggested by several ecological modelers (e.g., King and Neilson 1992, Smith and Shugart 1993). This scenario is named "dieback."

The second scenario entails only an impact on the regenerative capacity of timber stocks. As lands are predicted to become suitable for new timber species, the old types are able to continue growing where they currently exist, but they cannot regenerate. Thus, as these stocks are harvested, or as they die naturally, new types must migrate into the areas or be artificially regenerated in order for a new stand to be established. This transition implies that stocks which convert from one ecosystem type to another do so slowly, under the processes of competitive displacement. This scenario is named "regeneration."

In addition to changes in the area of ecosystems, changes in NPP imply changes in the growth functions of timber types. This paper assumes that timber yield functions change proportionally to the change in NPP predicted by

Table 1.—*Global results of the BIOME3 model with the Hamburg T-106 and the Schlesinger doubled CO_2 climate experiments*

Forested biome	Hamburg T-106			Schlesinger		
	Proportion changing	Relative size	NPP % change	Proportion changing	Relative size	NPP % change
Boreal deciduous	0.65	0.62	180	0.30	2.45	143
Boreal coniferous	0.31	1.08	12	0.42	1.36	7
Temp.-boreal mixed	0.36	1.41	12	0.74	0.53	1
Temp. conifer	0.46	1.53	17	0.79	1.07	17
Temp. deciduous	0.20	1.71	20	0.67	0.68	19
Temp. broadleaf evergreen	0.12	1.31	28	0.56	1.04	19
Tropical seasonal	0.13	1.50	43	0.33	0.89	25
Tropical rain	0.09	1.09	37	0.20	0.93	24
Tropical deciduous	0.20	2.37	41	0.62	0.98	23
Total forest	0.28	1.30	44	0.52	1.00	18

BIOME3 for the given timber type. Furthermore, annual changes in NPP are assumed to occur proportionally to changes in climate. Note that only the future growth of timber stocks is affected by this change. Existing stocks of timber are given at the time when climate change begins affecting timber, and they are not affected by the changes in growth rates.

ECONOMIC MODEL

The economic model combines two earlier efforts: Sedjo and Lyon's TSM model (1990) and Sohngen and Mendelsohn's (1998) recently developed model of timber markets in the US. This economic model is described more thoroughly in Sohngen *et al.* (1997). In order to capture optimal economic adaptation to large scale ecological adjustment, the model utilizes a forward looking optimal control framework. As climate changes, foresters will respond to changing ecological conditions along a continuum of economic margins, shifting production from one region to the next as forest stocks respond to external stimulus.

Like the earlier two efforts, the objective of the timber market model is to maximize the net present value of net surplus in industrial wood markets. Timber is broken into age classes, which are followed through time. In addition, regeneration and management intensity are optimally chosen in each period when trees are planted. This model, however, incorporates several important improvements to the earlier models. First, it incorporates 46 different timber classes allocated into five broad management classes. Timber and management classes describe the location of important species across the globe, and they are linked to the ecosystem types described above. Second, the model endogenously determines harvests in both northern and tropical inaccessible regions, and it endogenously determines annual additions to tropical timber plantations. Thus, during climate change, the model will optimally adjust four margins: regular harvests, harvests in inaccessible lands, plantation establishment, and timberland management in regular types across the globe.

EMPIRICAL RESULTS

In this section, we present the results of the ecological-economic model. Baseline harvest and management patterns are predicted first. Then, the ecological results from the BIOME3 model under two climate change scenarios are linked to the economic model. Shifts in harvest and management patterns are predicted and discussed relative to the baseline case.

While the BIOME3 model predicts substantial forest loss during climate change (the "shifting proportion" column of table 1), economic adaptation and adjustment limit many of the economically harmful impacts of these changes. Figure 1, for example, shows predicted baseline and climate change prices. Global prices are lower than the baseline throughout the transition and into the long term. The long term results are driven by fairly large increases in timber growth predicted by BIOME3. Even though the model accounts for salvage from some regions, the dieback scenario predicts higher prices during the early periods because the value of salvage stocks is lower than the value of stocks that have been harvested from lands that do not experience dieback.

Potentially more important changes in regional harvests underlie these general results. Table 2 presents the change in timber harvests, averaged over both the dieback and regeneration scenarios for each of nine regions. Timber yields increase in all regions, except Oceania (Australia

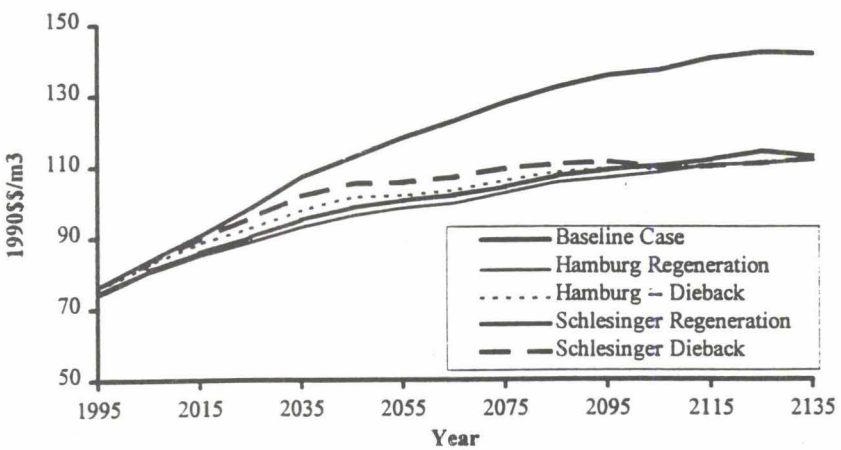

Figure 1.—*Global price paths for the baseline and climate change scenarios.*

and New Zealand) for the Hamburg T-106 climate change scenario. In general, timber yields increase more in the developing regions than developed regions, leading to a greater overall response from those regions.

These changes, however, are not constant over time. North America, for example, experiences a decline in timber production during the first 50 years, when climate change causes substantial redistribution of existing biome and timber types. Although the Former Soviet Union (FSU) experiences similar ecological changes, dieback occurs largely in inaccessible regions. The FSU takes advantage of these changes to shift additional inaccessible land into more productive accessible types. This leads to substantial long term gains in timber production for that region.

Timberland management also shifts among regions as the underlying productivity of timberland and prices change over time. The combined impact of these adjustments leads to greater management intensity in the emerging region, but less in the temperate zone (table 3). Large changes in biome distribution in the temperate zone reduce the incentive to manage in those regions, while the smaller changes in the subtropical regions allow management intensity to increase in emerging plantations. This adjustment has a substantial impact on global timber markets during climate change because plantations grow relatively quickly. Eucalyptus plantations, one of the most widely distributed, can be planted and grown to maturity for markets in 7-15 years, a time frame that allows several generations of eucalyptus to be planted and harvested when stocks are undergoing substantial changes in the temperate zone.

Markets also shift the overall level of plantation establishment in the emerging region. The level of land available for forested plantations depends on current marginal land rental and plantation establishment costs relative to the discounted marginal benefits of adding new land today. Because plantations can enter and leave the global forest land base, the area of land in plantations increases initially relative to the baseline in both climate change scenarios and declines later in the model run (table 4). Plantations are used in the earlier time periods to mitigate dieback in the temperate zone, but over the long term, the area of land in plantations does not expand because prices are lower and management intensity has increased.

Finally, one must account for shifts in harvests at extensive margin. The effect of ecological changes on markets leads to higher harvest of some extensive forest lands during climate change, particularly the boreal regions (fig. 2). During dieback, harvests expand relative to the baseline because these lands serve as stocks which can be used to mitigate the effects of dieback elsewhere. The heaviest additional harvests come from the FSU boreal region because that region experiences fairly large increases in timber growth (49 to 69 percent) and the conversion of boreal inaccessible forests to more accessible types is highly profitable during climate change. Note that this change is not driven by dieback, because we do not allow for salvage in extensive margin forests during climate change.

CONCLUSION

This paper presents the results of the ecological-economic modeling effort to assess the impacts of climate change on global timber markets. The paper begins with a description of steady state ecological models used for predicting impacts of climate change on forest biome

Table 2.—*Change in timber production relative to the baseline for nine regions of the globe for both doubled CO_2 climate experiments*

	Hamburg T-106			Schlesinger		
	1990-2040	2040-2090	2090-2140	1990-2040	2040-2090	2090-2140
A. Developed						
North America	(0.02)	0.12	0.31	(0.02)	0.15	0.29
Europe	0.05	0.01	0.17	0.10	0.14	0.22
FSU	0.06	0.18	0.71	0.03	0.08	0.93
Oceania	(0.03)	(0.05)	(0.10)	0.12	0.33	0.36
B. Developing						
South America	0.19	0.47	0.50	0.10	0.22	0.20
China	0.11	0.29	0.31	0.10	0.27	0.27
India	0.22	0.55	0.58	0.14	0.30	0.29
Asia-Pacific	0.10	0.30	0.36	0.04	0.14	0.17
Africa	0.14	0.41	0.42	0.05	0.17	0.11
Total	0.06	0.21	0.31	0.05	0.18	0.29

Table 3.—*Average changes in management intensity of newly planted lands for the dieback and regeneration scenarios*

	Regeneration		Dieback	
	Temperate	Emerging	Temperate	Emerging
A. Hamburg T-106				
1990 - 2020	0.86	1.03	0.86	1.09
2020 - 2050	0.91	1.06	0.96	1.12
2050 - 2080	0.96	1.05	0.97	1.09
2080 - 2110	0.91	1.05	0.94	1.05
2110 - 2140	0.84	1.01	0.80	1.03
B. Schlesinger				
1990 - 2020	0.84	1.00	0.82	1.08
2020 - 2050	0.92	1.00	0.93	1.08
2050 - 2080	0.83	0.98	1.05	1.02
2080 - 2110	0.92	0.94	0.92	0.95
2110 - 2140	1.09	0.89	0.88	0.94

Table 4.—*Area of emerging region plantations for two climate change scenarios relative to the baseline*

	Hamburg T-106		Schlesinger	
	Regeneration	Dieback	Regeneration	Dieback
2020	1.01	1.03	1.00	1.02
2050	1.02	1.05	1.00	1.03
2080	1.01	1.03	0.99	1.01
2110	1.01	1.02	0.97	0.98
2140	1.01	1.02	0.97	0.97

distribution and NPP. Two transient models of ecological change are then developed which allow us to model the natural response of ecosystems to climate change. The transient results are then linked to an economic model of timber markets to determine the human response to these changes.

The ecological-economic model predicts that markets are likely to benefit from the changes predicted by the BIOME3 model. In the long term, the area of forests and NPP increases in general, leading to lower steady state price levels. While steady state results are interesting, the ecological models predict fairly substantial transient effects. The modeling system predicts that markets will shift harvests and management from region to region to adjust and adapt to these large scale changes.

The transient adjustments of markets shift harvests and management towards the emerging plantation region. Even in the baseline, global harvests shift strongly in this direction, but the climate change scenarios examined here suggest that these changes will be strengthened. Management in the emerging region is also enhanced relative both to the baseline and the temperate region. This occurs because these regions are less susceptible to climate change during the transition period.

Two stocks of timber prove crucial during the adjustment to climate change, emerging region plantations and inaccessible regions. The inaccessible stocks of the Former Soviet Union are perhaps the most important, as harvests there respond strongly to changes in timber growth and dieback. The effect of these two changes enhances the long term FSU response to climate change.

It is important to note that these results are broadly consistent with those presented in Sohngen and Mendelsohn (1998) for the United States. While that paper did consider a large set of ecological results, it was limited in that it considered only the United States. This paper contains only a limited set of possible ecological results, but it captures the global market adjustment. Further analysis should attempt to incorporate a broader array of ecological results.

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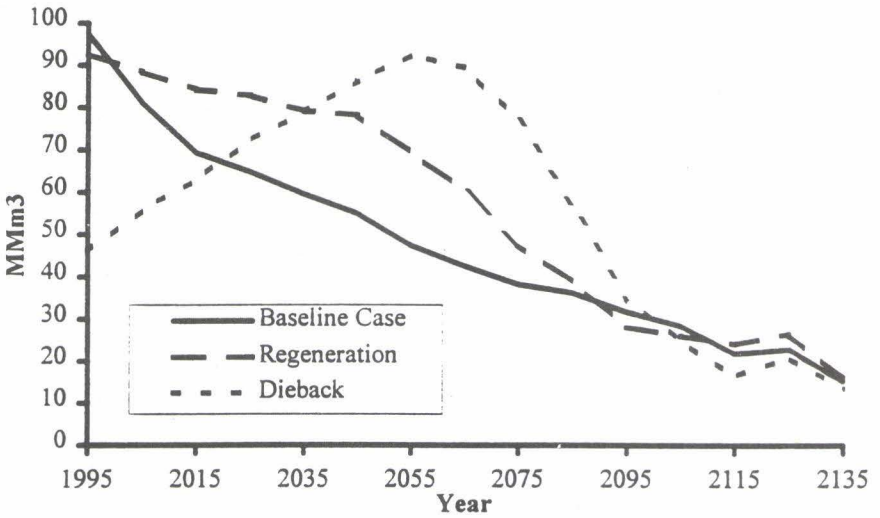

Figure 2.—*Harvests in the northern extensive margin for the baseline case and the dieback and regeneration scenarios in the Hamburg T-106 scenario.*

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WINDTHROW ECONOMICS AT THE FOREST LEVEL IN THE CANTERBURY REGION, NEW ZEALAND

H. Bown and E.M. Bilek[1]

We manage natural systems that are inherently unstable and unpredictable, yet seek to impose on them something they cannot be.

–Mike Dombeck, Chief
U.S. Forest Service
8 April, 1997

ABSTRACT.—The problems of forest estate valuation and harvest scheduling under risk of occurrence of catastrophic events were examined. An optimization and simulation model were used sequentially to test the robustness of management strategies. The optimization model provides an optimal harvest pattern under deterministic conditions. The simulation model modifies the optimal harvest pattern according to a function of random risk, assessing the robustness of the strategy through net present value (NPV). A large number of runs provides estimates of mean, standard deviation and a frequency distribution for NPV. The model uses data from a plantation forest estate of 8,412 ha located in Canterbury, New Zealand that has been subject to periodic catastrophic windthrow. Incorporating wind risk reduced the NPV after taxes of the Canterbury forest estate by 11 percent on average, compared with a deterministic solution. Estate value was not highly sensitive to moderate changes in windthrow frequency. The results of the stochastic simulation were similar to those in an optimized solution under risk, suboptimizing by no more than 3 percent.

INTRODUCTION

Forestry is important to New Zealand, currently accounting for 6.9 percent of New Zealand's GDP (New Zealand Forest Owners' Association 1996). Plantation forests account for 99.3 percent of the roundwood removals in New Zealand (Ministry of Forestry 1996). Harvests are currently at 17.2 million cubic meters (m^3) (Ministry of Forestry 1996) and are projected to increase to 25 million m^3 by the year 2010 (New Zealand Forest Owners' Association 1996).[2] Risks affecting the plantations affect the entire forest industry.

Wind is the most important risk factor affecting New Zealand's plantations. Wind damage is far more important than fire, which accounts for only a small proportion of the total annual damage in New Zealand's plantations (Somerville 1989). Windthrow, in contrast, has accounted for at least 50,000 ha of catastrophic damage to stands over 5 years old since the turn of the century (Somerville 1995).

The nature of the impact of wind on the plantations within New Zealand varies by region. While windthrow and stem breakage have occurred over a high proportion of the country, wind damage has been more accentuated in the Wellington, Canterbury, North Auckland, and Manawatu regions. Of these, Canterbury has suffered the most serious damage due to catastrophic loss (Sommerville 1989).

New Zealand lies within a belt of westerly winds circling the globe (Wards 1976). The most damaging winds in Canterbury come from the northwest. These are warm, dry (föhn) winds which, reinforced by the blocking effect of the Southern Alps, reach gale speeds (New Zealand Meteorological Service 1986). In August 1975, a 170 km/hr gust contributed to the blowdown of 6,000 ha.

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[2] *This forecast is conservative since it assumes no new planting. If an additional 50,000 ha/yr are planted, then the predicted annual harvest will increase to about 30 million m^3. New land is currently being planted at a rate of about 74,000 ha/yr (Ministry of Forestry 1996).*

Northwest gales, often preceded by heavy rain, have caused damage in Canterbury in 1914, 1930, 1945, 1956, and 1975. In 1968, a tropical cyclone producing strong southwesterly winds resulted in 1,000 ha of windthrow (Thompson 1976).

Such storms can flatten forests and cause large management and logistical problems. Due to a lack of suitable infrastructure, the timber blown down in the 1945 storm was only partially recovered. The timber blown down in 1975 resulted in special marketing strategies to export to Japan and China. In addition, domestic saw logs and poles were stockpiled under sprinklers for over 2 years (Turner 1989).

One local company reported that since the turn of the century, 90 percent of all timber harvested in the Canterbury plains has been following windthrow events (Studholme 1995). An examination of the age class distribution of a company's estate in the early morning and then in the afternoon of August 1, 1975 illustrates the impact of a major storm (fig. 1).

Note that stands under 15 years of age were not windblown, but that stands 30 years and older were almost completely windblown. The proportion of forest being windblown generally increases by age class. Wendelken (1966) reported scarce damage to plantations younger than 18 years after a 1964 storm in New Zealand. Similar trends have also been observed in the UK (Miller and Quine 1991).

Current models planning the evolution of forest estates usually address risk in a deterministic fashion (Somerville 1995). Risk is recognized through a constant average annual reduction in net stocked volume. Therefore, each year the forest area is reduced by a constant attritional factor representing the forest area that is partially or completely affected over the long term. Reed and Errico (1986) used this approach when dealing with fire risk in Canada. New (1989) reports that a 0.6-percent loss per annum due to wind has been used to account for windthrow in a New Zealand growth model. Sommerville (1995, p. 463) notes:

> With the exception of Canterbury, the regional average losses as catastrophic damage are quite similar at 0.20–0.26 percent of net stocked area lost per annum. Canterbury, however, has been subjected to very high levels of catastrophic damage.

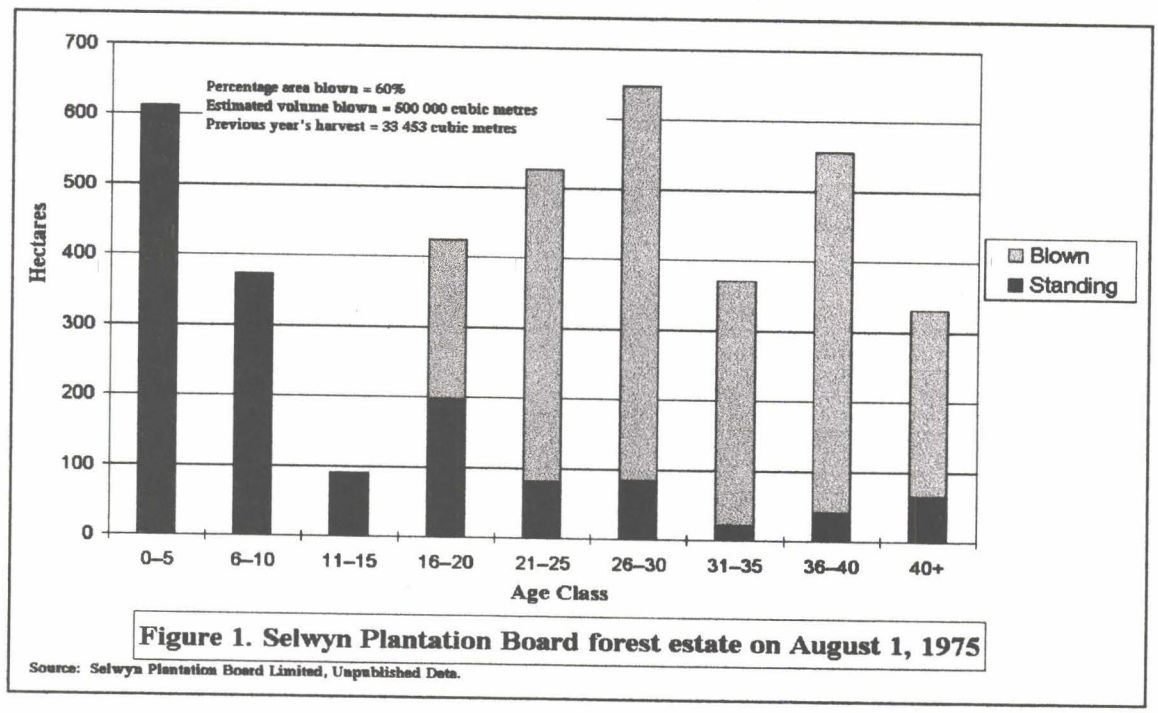

Figure 1. Selwyn Plantation Board forest estate on August 1, 1975

Source: Selwyn Plantation Board Limited, Unpublished Data.

Generalizations may be appropriate either over the entire country or over a long enough time period, or where wind losses are endemic, affecting a constantly small, predictable portion of the forest each year. However, such generalizations are not adequate in all regions. Nor are they adequate to assess the impact of major catastrophic events on an organization's financial or operational position over time. Because windthrow can result in sudden large economic losses and disrupt wood flows and harvest scheduling, tools are required that can aid decision-makers in understanding and managing such risks.

This paper examines the harvest scheduling problem at the forest estate level by including random risk, and compares the results with a deterministic solution in a case study.

MODELING METHODOLOGY

The methodology is divided in two parts: estate modeling and stochastic modeling. Estate modeling refers to the development of a mathematical model able to represent a forest estate over time. The stochastic component refers to a probability distribution function able to randomly represent the windthrow occurrence. Both components are integrated in order to achieve the research objectives. The system is shown in figure 2.

The models are compatible and use a common forest description. This description has two components: a forest estate description (areas by age class within crop types, yield and log assortment, costs, prices, and some financial parameters) and a probability distribution function regarding windthrow damage (occurrence and intensity).

Forest Estate Modeling

We used the forest description in a linear programming (LP) model in order to find an optimal solution, maximizing net present value (NPV). Standard constraints relating to conservation of area, as well as volume constraints and ending inventory constraints ensure that the resulting solution is believable. However, the LP model is deterministic; that is, it does not incorporate the random risk element of a major windstorm.

Stochastic Modeling

The simulation model reshapes the solution from the optimizer according to "proportional rates" regarding the distribution of storm damage; that is, if a random storm occurs in simulation, we assume stands will be damaged according to their age and in the same proportions that age classes of Selwyn Plantation Board Limited (SPBL) were damaged in 1975.

We used historical data from Canterbury to create a probability distribution function representing the damage caused by windthrow at the forest level. The function describes frequency of occurrence and intensity of windthrow over time. We developed this function based on the approaches followed by Reed and Errico (1986) in Canada and Manley and Wakelin (1989) in New Zealand.

Occurrence is the time interval between two successive catastrophic windthrow events. This time span is obviously not a constant behaving as a random variable. However, we assume an average return period in order to represent the phenomenon in the long term.

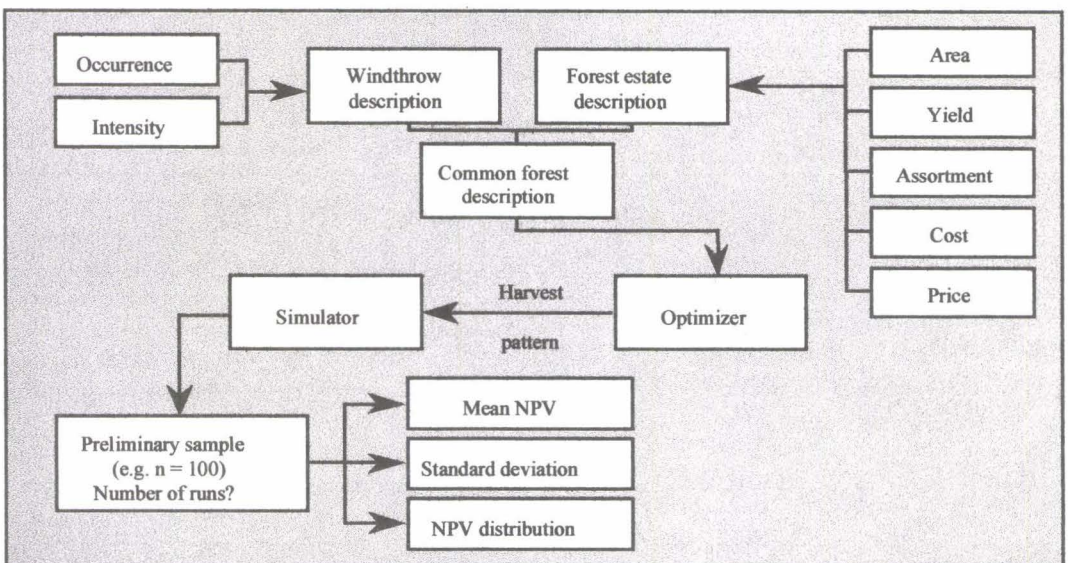

Figure 2.— Description of a proposed system to address catastrophic risk at the forest level

Data recording gust speeds for New Zealand extends back only to 1919. Therefore, we cannot statistically estimate an average return period for major wind events. SPBL, a major forest owner in Canterbury, uses a 28-year return period for its silvicultural planning (Studholme 1996, pers. comm.), so we chose this for an average return period of major storms, testing it later in a sensitivity analysis.

Buongiorno and Gilless (1987) proposed an exponential probability distribution function to represent the occurrence of catastrophic events that have the same chance of occurring, regardless of when the previous event happened. If T is the time interval between two wind storms, and m is the mean rate of catastrophic wind storms, then the probability P of having a storm during a time period t is:

(1) $P(T^2\ t) = 1 - \exp(-mt)$

We used this function to generate random time intervals between two successive catastrophic events that, after a large number of observations, are equal to the average return period. This is accomplished by adding a random number, R, and rearranging (1) to solve for the time period:[3]

(2) $$t = -ln\frac{(1-R)}{m}$$

In any given year, the probability of a major windstorm is a small constant. However, as the time span to be considered increases, the probability of a major windstorm occurring during that time span also increases. This relationship may be seen in figure 3.

Function (2) is used as many times as necessary over the planning horizon in order to provide a frequency distribution for the desired planning variable. For this analysis, we chose NPV as the planning variable. As a result we can foresee not only the expected value of the decision criterion but also the likelihood of realizing a much higher or a much lower value. If the calculated NPV's are normally distributed or symmetrical about the mean, then a t-distribution may be used to approximate the distribution (Gottfried 1984).

Determining the number of random events required for the desired confidence level is a two-step process. First, a trial is run with 100 simulations and its mean and standard deviation are calculated. Then, based on these statistics, the desired confidence interval for the mean and the number of simulations required to achieve this may be estimated based on the t-distribution (Gottfried 1984).

(3) Number of observations required

$$n = \left(\frac{t * s}{x * \bar{Y}}\right)^2 + 1$$

[3] *See Buongiorno and Gilless (1987) p. 216-217 for full details.*

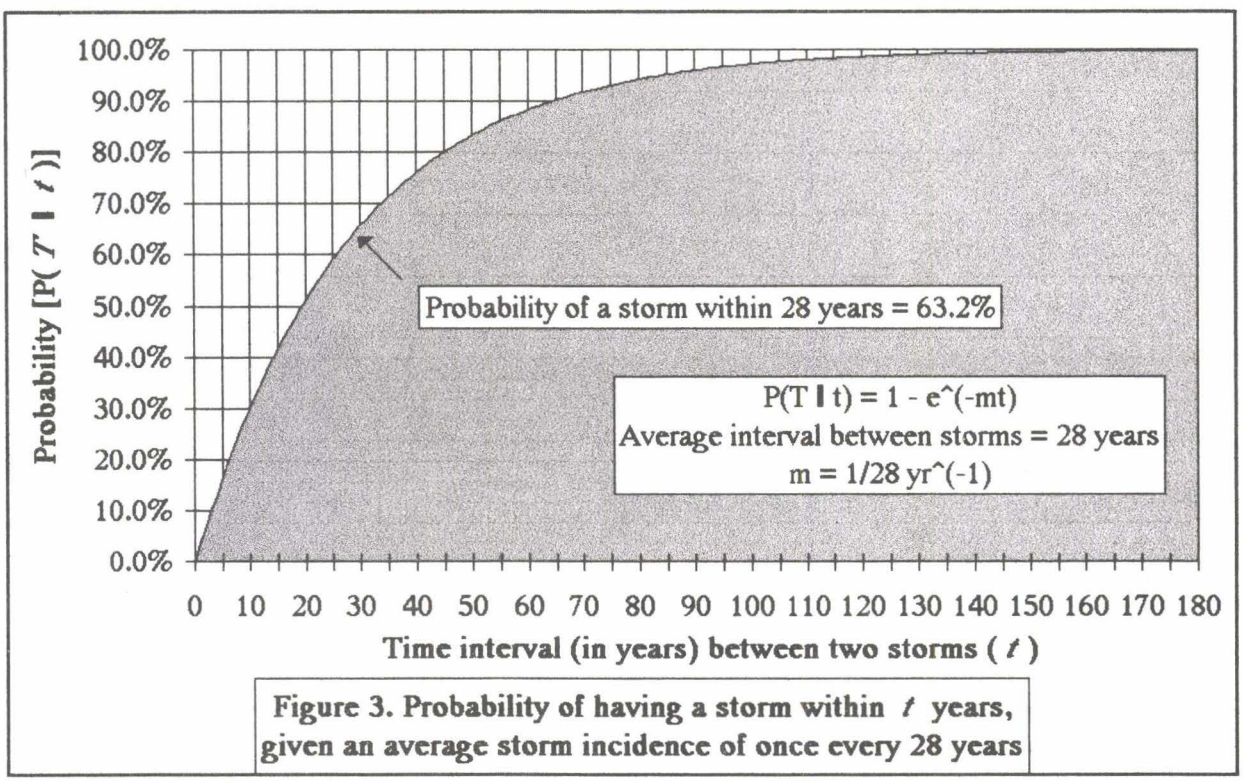
100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Probability [P(T ❙ t)]
Probability of a storm within 28 years = 63.2%
P(T ❙ t) = 1 - e^(-mt)
Average interval between storms = 28 years
m = 1/28 yr^(-1)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
Time interval (in years) between two storms (t)

Figure 3. Probability of having a storm within t years, given an average storm incidence of once every 28 years

where:

t = the t-statistic based on the desired confidence level
s = the calculated standard deviation for the NPV in the trial run
x = desired percentage range for the mean (e.g., 0.01 is ± 1 percent)
$\bar{Y}$ = the calculated mean for the NPV in the trial run

While our distribution is not symmetrical about the mean, we took the results of this formula and arbitrarily doubled the number of simulations to ensure we had an adequate number of runs.

CASE STUDY

We ran the model using data for a portion (8,412 ha) of the forest estate owned by SPBL. SPBL is a local authority trading enterprise, which is essentially a limited liability company owned by local government organizations. SPBL's estate is mostly *Pinus radiata* D.Don (radiata pine) planted largely in the Canterbury Plains.

We made several assumptions to simplify the study:

- All simulations were over a 50-year planning horizon;
- Time was aggregated into 5-year periods in order to reduce the number of decision variables and because the model assumes that the period of recovery is the same as the aggregation of time;
- There is no price penalty for timber blown down and harvested in relation to unblown harvested timber.
- Twenty percent of the timber volume was assumed to be lost due to windthrow;
- We only attempted to model SPBL's radiata pine. This species makes up 90 percent of SPBL's estate.
- Costing was kept constant.[4]

We used volume and regulation constraints in optimizing the harvesting scheduling problem. We constrained volume so that from one period to the next, it did not vary more than 10 percent. We set up regulation constraints to achieve at least 1,500 ha in each of the first four age classes at the end of the planning horizon. The optimized solution produced an NPV after taxes of $43.208 million. However, this value does not include windthrow risk.

We used a preliminary sample of 100 runs to estimate that approximately 550 runs were required to return a 95 percent confidence interval. We arbitrarily doubled this to ensure that we achieved an adequate confidence level. The average NPV after taxes under stochastic conditions was $38.278 million, an average reduction of 11 percent over the deterministic case. The minimum value was $24.152 million and the maximum was $43.301 million.

The frequency distribution of these stochastic NPVs by $2 million classes is shown in figure 4. This does not follow a normal distribution. The overall trend is increasing in relative frequency (probability) from left to right, which means that there are better chances in getting NPVs closer to the stochastic maximum than to the stochastic minimum.

[4] *These costing, price, and timber recovery assumptions were based on personal communications with staff from Selwyn Plantation Board Limited.*

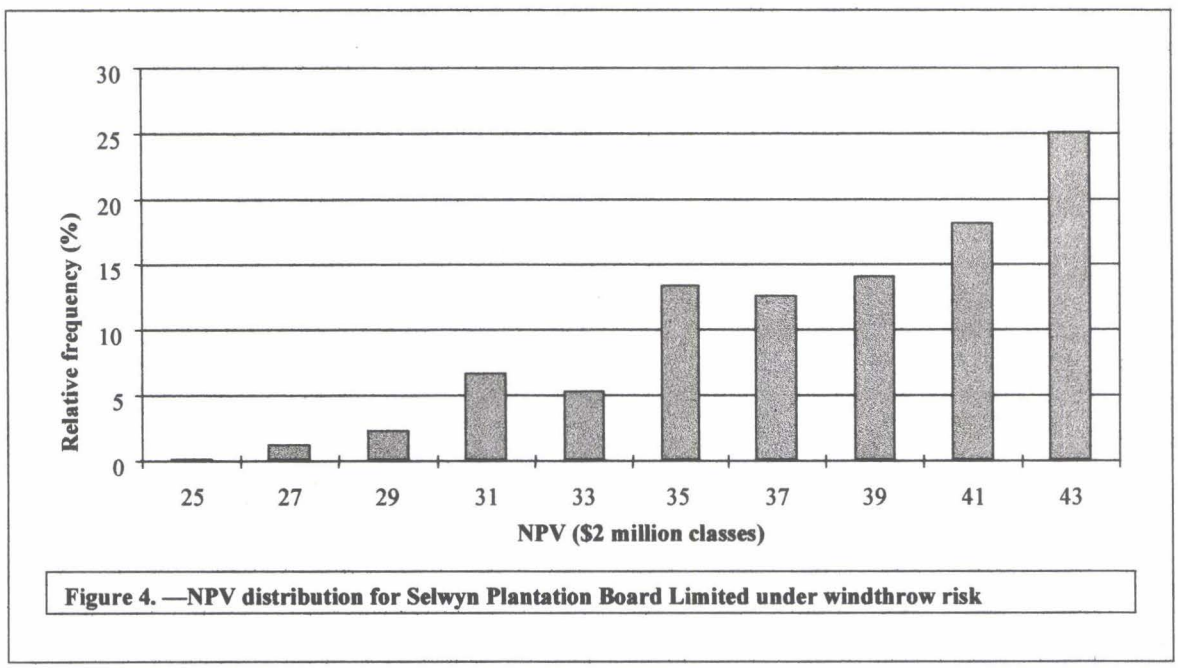

Figure 4.—NPV distribution for Selwyn Plantation Board Limited under windthrow risk

The lowest NPVs relate to cases in which there are frequent windthrows early in the planning horizon. In the case where no windthrow takes place, the stochastic solution is identical to the deterministic solution. Curiously, there are cases where the stochastic NPV is higher than the deterministic NPV. This is due to the regulation constraints in the optimization and to the way we have calculated NPV in the objective function. We have included only cash flows in the formulation and a value for the residual forest area. There are simulation runs in which the only windthrow occurs late in the planning horizon. These cases allow more fallen timber to be recovered in the final periods than would be allowed under deterministic conditions.

SENSITIVITY ANALYSIS

We ran sensitivity analyses on the significant variables in the analysis; that is, establishment costs, prices, recovery assumptions, and return period for the windstorms. Changes in NPV due to changes in the first three variables are shown in table 1.

Table 1.—*Decrease in NPV due to a 1-percent change in selected variables*

Variable	Decrease in NPV
	Percent
Establishment cost increases	0.22
Log price decreases	.40
Recovery factor decreases	.50

We also analyzed the sensitivity of the solution in relation to the return period. We varied the average return period by 5 years and by 10 years. Varying the return period by 5 years had little impact on NPV. NPV decreased by 1.8 percent given a 23-year return period and increased by 1.7 percent given a 28-year return period. Varying the return period by 10 years had more of an impact. NPV decreased by 4.6 percent given an 18-year return period and increased by 3.0 percent given a 38-year return period.

COMPARISON BETWEEN SIMULATION AND OPTIMIZATION

While simulations are useful to illustrate the risk associated with forestry, they do not produce an optimal solution. In order to test the degree of suboptimality, we compared the suboptimal solution provided by the simulator with a reoptimized solution following simulated windthrows in two selected runs. Both had only one windthrow in the planning horizon. In the first run, the windthrow occurred early. In the second, the windthrow happened more towards the middle of the planning period. There was very little difference in the resulting net present values.

Where windthrow occurs early, the difference between the two methodologies is greater. However, even if the windthrow occurs early, the difference between the simulation results and reoptimized results is small.

DISCUSSION

This study demonstrated a methodology for examining the wind risk associated with a forest estate. It is a relatively simple combination of models. A model able to reoptimize between windthrow events would be more accurate than the model proposed here. However, such a problem becomes more complex and takes much longer to solve. We do not feel that the added complexity is justified by the added accuracy.

There were not large differences between the NPV produced by optimization and the average NPV produced by simulation incorporating windthrow risk. Part of the reason for this is the assumptions regarding recovery and the length of time over which fallen trees may be recovered. Canterbury has relatively high recovery rates and blown-over trees remain harvestable for a relatively long time. Silviculture in Canterbury has been adapted to accommodate the northwest winds.[5] Trees are planted and roading is designed with the expectation that the trees will be blown over during the rotation. There is no

[5] *See Studholme (1995) for a detailed description of the silviculture adopted.*

Table 2.—*Difference in NPV between a sub-optimal simulation and an optimization in two selected stochastic runs*

Year of windthrow	Simulation	Optimization	Percent difference
	- - - - - -Million dollars- - - - - -		
2	30.322	31.009	2.2
18	38.627	38.639	0.003

deep ripping and no high pruning in the plains because when the wind does come, it is preferable that the trees blow over rather than snap off. If they blow over and take a root plate with them, they can stay alive for up to 5 years.

There were not large differences between the deterministic and average stochastic NPVs, but this does not mean that the simulation is a waste of time. The simulations do provide decision-makers with an idea of the range of achievable NPVs and also provide a quantification of the degree of risk that the enterprise is bearing. Simulation can be used to give an idea of the magnitude of the events.

The simulations can also provide decision-makers with an idea of the importance of various factors in the profitability of their operations following windthrow. For example, in these runs we found that while NPV was not very sensitive to the average return period of the wind, it was highly sensitive to the recovery factor and to establishment costs. Two ways to increase NPV would be to improve the recovery factor by finding suitable use for broken trees (chips, poles, pulp logs, small saw logs, etc.), or to adopt new establishment techniques aimed to reduce costs.

This is a first step in modeling wind risk at the estate level. The modeling system could be modified and improved. Additional species could be incorporated along with their relative susceptibility to wind. Models could consider tree thinning since trees that have just been thinned tend to be very susceptible to wind for a few years until they become windfirm. Impacts of defects later appearing in trees that were not blown over could be incorporated. Further study of the conditions under which trees are blown down could lead to more accurate predictive models of which stands will blow down and under what conditions. The goal of this model and any future improvements is to provide managers and investors with tools that can help them to better understand and manage the risks they take in forestry.

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A COMPUTER SIMULATION MODEL OF JACK PINE BUDWORM IMPACT IN MICHIGAN'S UPPER PENINSULA

Bradley E. Conway[1], Larry A. Leefers[1], and Deborah G. McCullough[1,2]

ABSTRACT—Periodic outbreaks of the jack pine budworm (*Choristoneura pinus pinus* Freeman) can result in significant volume losses in jack pine (*Pinus banksiana* Lamb.) forests. To predict these losses and to help managers make informed decisions, we developed a simulation model of jack pine budworm impact. The stand-level model was built in Stella II™ using growth equations from the TWIGS growth and yield model and data from a recent outbreak in the Hiawatha National Forest. The model uses readily available inputs and produces estimates of volume and economic loss. The model allows the user to alter management decisions and evaluate the effects of these strategies.

INTRODUCTION

The jack pine budworm (*Choristoneura pinus pinus* Freeman) is a small needle-feeding caterpillar that feeds almost exclusively on jack pine (*Pinus banksiana* Lamb.) (Howse 1984). Periodic outbreaks of this native North American insect occur every 6 to 10 years and last for 2 to 3 years (Volney 1988, Volney and McCullough 1994). Defoliation usually results in reduced growth, damage to the tree's terminal leader (top-kill), and tree mortality (Kulman *et al.* 1963, Cerezke 1986, Gross 1992, McCullough *et al.* 1996). Significant losses in merchantable volume of jack pine can result from a single jack pine budworm (JPBW) outbreak (Gross and Meating 1994).

Due to economic and environmental considerations, forest managers in the Lake States are unable to use insecticides to combat JPBW infestations. Instead, managers rely on silvicultural treatments, harvest scheduling, salvage, or cover-type conversion to minimize the timber losses associated with an outbreak (Heym *et al.* 1993). Forest managers must work under increasing pressure to maximize all benefits from forested land, including benefits from wildlife habitat protection and recreational use. Faced with these often conflicting goals, decision makers need special tools to help allocate resources efficiently and to explain their decisions to the public.

In this paper we describe a computer simulation model of the biological and economic impacts of JPBW outbreaks. This model is a starting point for developing a tool that can be used by managers to help make and justify management decisions. We will discuss the methods used to build the model and some preliminary testing of the model. Finally, the role of models such as this in the development of pest management decision support systems is addressed.

CONCEPTUAL MODEL

The model was constructed in Stella II[3] (High Performance Systems, Inc., Hanover, NH). Stella II is a software package designed to facilitate the construction of dynamic systems models. Stella II™ provides a simple set of building blocks that can be used to visually represent components of the system. Model components are visually linked in a hierarchical environment. Stella II allows the user to run simulations, create tables and charts of model variables and simulation results, and construct a graphical user interface (GUI) to control model inputs.

The model is based on a with/without comparison in which the user sets values for basic stand variables that determine the characteristics of a pure, even-aged jack pine stand. The model generates two stands that are initially identical and projects each to a future year specified by the user (fig. 1). The only difference between these two projections is that trees in one stand

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[3] *Stella II™ is a registered trademark of High Performance Systems, Inc.*

(the outbreak stand) suffer periodic reductions in volume due to JPBW attacks. At the end of the simulation, a comparison of the merchantable volume and economic value of each stand provides an estimate of the JPBW impact on the timber resource.

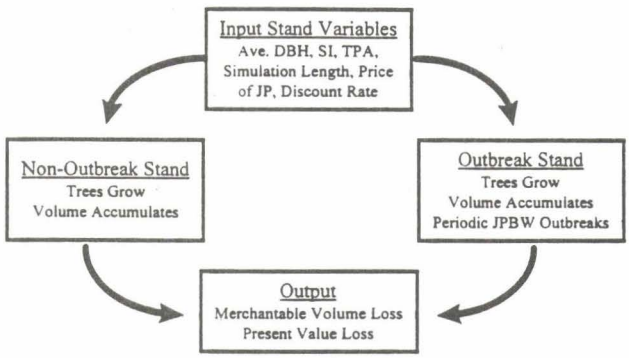

Figure 1.—*Conceptual model diagram. DBH = diameter at breast height, SI = site index, TPA = trees per acre.*

In both the outbreak and non-outbreak scenarios, stand growth is a composite of growth from seven individual-tree diameter classes. Each diameter class represents an initial percentage of the total number of trees per acre. Jack pine is typically found in even-aged stands (Benzie 1977), and a frequency distribution of the diameter classes in an even-aged stand is likely to be normal (Smith 1986). Therefore, the trees per acre in each diameter class represent a portion of the total trees per acre that corresponds to this normal distribution. Tree growth, mortality, and volume are calculated using the same equations for each diameter class.

NON-OUTBREAK GROWTH AND MORTALITY

Trees in each diameter class grow in diameter at breast height (DBH) and height over the course of the simulation. The equations that determine both DBH and height growth were taken from a USDA Forest Service growth and yield model, the Lake States TWIGS variant of the Forest Vegetation Simulator (LS-TWIGS) (Miner *et al.* 1988, Bush and Brand 1995). LS-TWIGS is a distance-independent, individual-tree growth model applicable to a number of Lake States tree species, including jack pine. Miner *et al.* (1988) noted that the LS-TWIGS equations represent the growth of jack pine trees well and have basic, readily available inputs (e.g., DBH and site index). Cubic foot volume equations were also taken from LS-TWIGS. Each diameter class has an associated mortality rate that reduces the number of trees per acre over time in that diameter class; this mortality is based on equations reported in Buchman *et al.* (1983). We assumed that no ingrowth (i.e., reproduction, seedling establishment and growth) will occur during the simulation.

OUTBREAK GROWTH AND MORTALITY

The model allows the user to select a deterministic or stochastic outbreak sequence. The deterministic outbreak sequence simulates outbreaks during the same years in each simulation. We based the deterministic sequence on the pattern of JPBW infestations that have occurred in Michigan over the past 46 years; the Michigan Department of Natural Resources' annual forest pest reports provided this historical pattern. The deterministic outbreak sequence allows the user to alter stand inputs or to compare different stands under the same outbreak sequence. The stochastic outbreak sequence simulates outbreaks in a random, periodic sequence every 6 to 12 years.

Data for quantifying the reduction in volume likely to occur as a result of a JPBW outbreak came from field studies in the Raco Plains area of the eastern Hiawatha National Forest (fig. 2). The Raco Plains area is characterized by sandy glacial outwash soils and dominated by large areas of jack pine forest (Heym *et al.* 1993). From 1991 to 1993, a JPBW outbreak occurred in this area. Survey work has been performed in all jack pine-dominated stands in four USDA Forest Service management compartments in the Raco Plains area for the past 5 years (1992-1996) (McCullough *et al.* 1996). Annually, we have collected data on the amount of jack pine tree mortality and top-kill that has occurred as a result of the most recent outbreak.

In 1992 we observed tree mortality to be only 1 percent. This is what we would expect endemic tree mortality to be. Outbreak-affected tree mortality increased dramatically in 1993, 1994, and 1995 then leveled off in 1996 (McCullough *et al.* 1996). This suggests that a JPBW outbreak affects tree mortality for 3 years and that a time lag exists between the start of the outbreak and the onset of outbreak-affected mortality. Predictive equations for annual outbreak-affected mortality were derived from these data using least squares linear regression. Mortality was determined to be a function of site index and stand basal area.

A thorough examination of the length of dead tops on top-killed trees revealed that rarely does the dead wood in the top-kill affect the amount of merchantable volume in a tree. Other studies have reached the same conclusion regarding top-kill (e.g., Gross and Meating 1994). For these reasons and for simplicity, we did not simulate top-killed trees in the model.

To evaluate the growth loss that has resulted from the most recent JPBW outbreak, we selected 60 live dominant or codominant jack pine trees at random from the Raco Plains study site in 1996. These trees were selected from stands that represented a range of all possible age,

site quality, and stocking combinations. We felled and removed discs at intervals along the stem of each tree.

To measure annual ring width, we dried, sanded one face, and located two average radii on each disc. We measured and cross dated annual ring widths along these radii to the nearest 0.01 mm using an optical digitizing scanner and WinDENDRO™[4] image analysis software (Regent Instruments, Inc., Quebec, Qc). We used this measurement data to plot mean annual ring widths of each disc against year of ring formation and noted JPBW outbreak and recovery years in this graphical analysis (fig. 3).

To estimate radial growth loss, we used only the breast height disc and followed a method similar to that used to evaluate growth loss of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) defoliated by western spruce budworm (*Choristoneura occidentalis* Freeman) (Thomson and Van Sickle 1980, Alfaro *et al.* 1982). We

[4] *WinDENDRO is a registered trademark of Regent Instruments, Inc.*

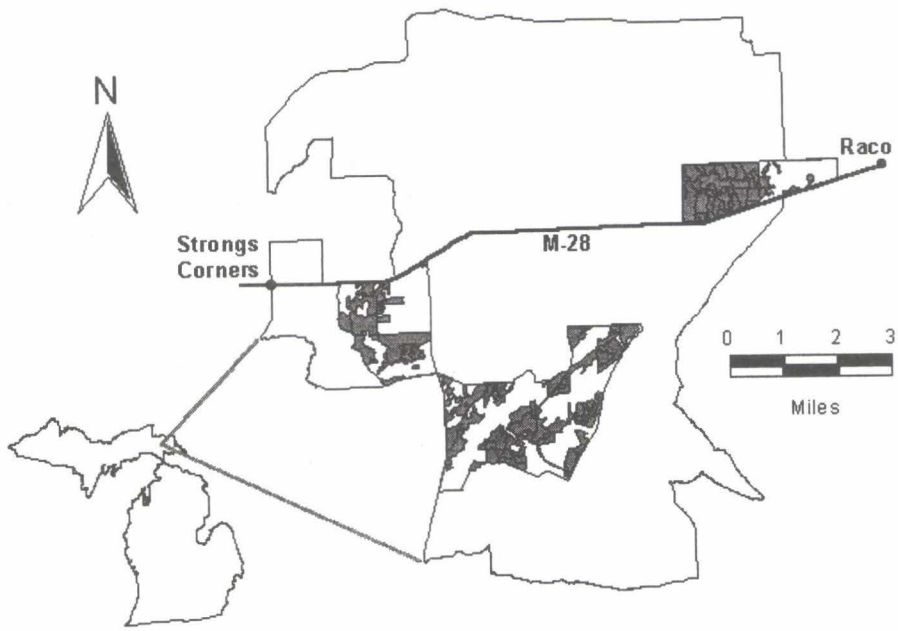

Figure 2.—*1996 sample stands in the Raco Plains area of the Hiawatha National Forest.*

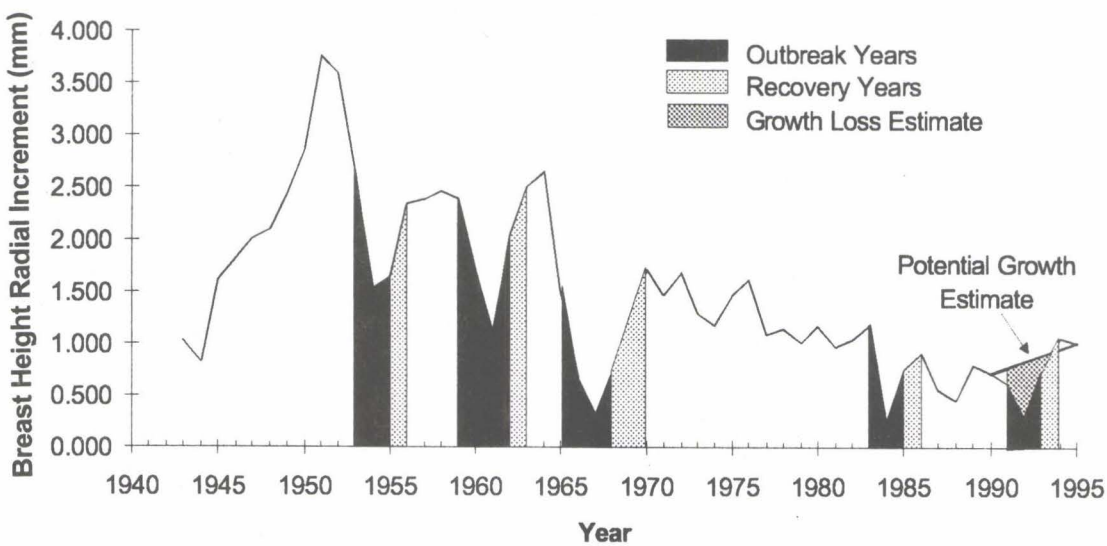

Figure 3.—*Annual radial increment at breast height of a single sample jack pine with historical JPBW activity highlighted.*

began by calculating the mean annual increment for the 5 years before the 1991-1993 JPBW outbreak (1982, 1987-1990) for each sample tree. Growth in 1983-1986 was not included in this calculation because there was a JPBW outbreak and recovery during this period. This 5-year mean and the 1995 increment (after recovery) were used as end points (set at 1990 and 1995, respectively) to determine a line segment that represented potential growth in the absence of the outbreak (fig. 3). The equation of this line segment was then used to calculate potential growth for 1991-1993 (outbreak) and 1994 (recovery) for each sample tree. Growth loss attributable to the most recent outbreak was estimated by subtracting the potential values from the observed values for the outbreak-affected years. If the observed value was greater than the predicted value, then we assumed that the growth loss was zero. Predictive equations for annual growth loss for the outbreak-affected years were determined by least squares linear regression. Growth loss was determined to be a function of tree DBH, site index, and crown ratio.

Although an actual JPBW infestation will only last for 2 to 3 years, an outbreak will affect radial growth and tree mortality for a longer period of time (Kulman *et al.* 1963, Cerezke 1986, Gross 1992, McCullough *et al.* 1996). Each outbreak in the model affects the stand for 5 years. Radial growth is reduced in each of the first 4 years of an outbreak. The increased mortality associated with an outbreak occurs in the third to fifth outbreak-affected years. Outbreak growth loss and mortality for each of these years are determined by the regression equations described above. The mortality rate during the interval between outbreaks in the outbreak stand is equal to the mortality rate in the non-outbreak stand.

The model produces estimates of merchantable volume loss and present value loss by comparing the volume and value of the outbreak and non-outbreak stands at the end of the simulation. We assume that the user knows the price of jack pine pulpwood at the end of the simulation. Typically, management costs for jack pine are a function of the area of the stand and can be considered independent of the JPBW outbreaks (Heym *et al.* 1993). Therefore, costs are the same for both scenarios and are assumed to have no effect on the determination of the present value loss.

MODEL VERIFICATION

Currently, data from other jack pine stands outside the area we surveyed are not available; however, additional data will be collected and used for validation in 1997. To evaluate the performance of the model, we selected a sub-sample of 25 stands at random from the Raco Plains sample stands that had both mortality and growth loss data. We ran each of these stands through a 6-year simulation with a JPBW outbreak beginning in year one and ending in year three. We did this in an attempt to simulate the 1991-1993 JPBW outbreak. We compared the annual and total percentage mortality predicted for each of the 25 simulations to the mortality observed in the field studies. Figure 4 shows the mean annual percent mortality resulting from a single JPBW outbreak as observed in the field and as predicted by the model. A one-way analysis of variance (ANOVA) indicated that there was no significant difference between the observed and predicted mortality for the 25 sample stands ($F = 0.298$; $P < 0.588$; $\beta = 0.083$ [total mortality]). Though results are not statistically different, figure 4 illustrates that the model consistently underestimated mean annual mortality slightly in each simulation year.

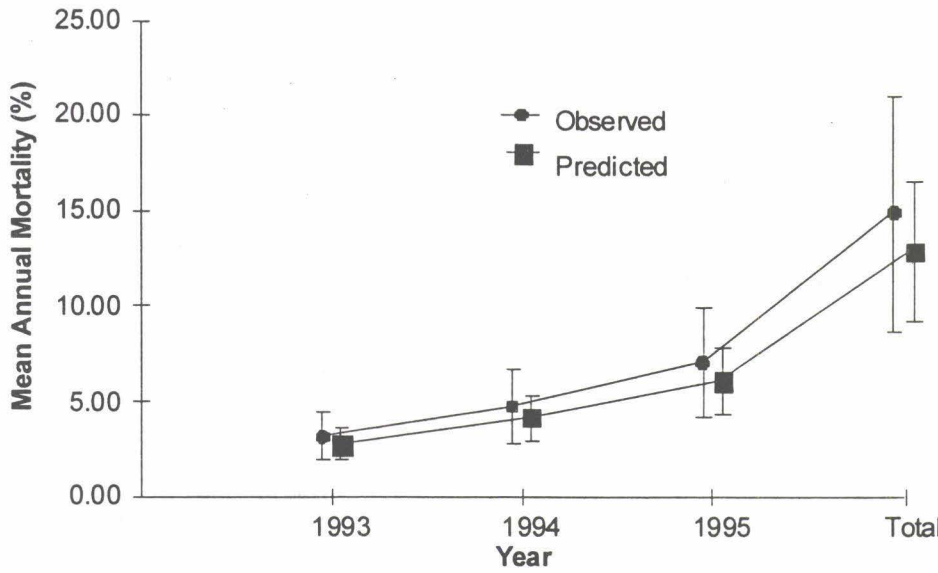

Figure 4.—*Predicted and observed mean annual percent mortality with 95 percent confidence intervals.*

To verify growth loss, we determined the diameter class that most closely resembled the sampled tree for that stand (i.e., the tree that was felled and measured). We selected the simulated growth loss for that diameter class and compared it to the observed growth loss. Figure 5 presents simulated and observed mean diameter growth loss for each year of the simulation. As with mortality, a one-way ANOVA indicated that there was no significant difference in any year between observed and predicted growth loss ($F = 0.124$; $P < 0.726$; $\beta = 0.064$ [total growth loss]). While there were no significant differences, the model slightly overestimated total growth loss attributable to a single JPBW outbreak.

Verification indicated that observed and predicted growth loss and mortality are very similar, but these results are not necessarily valid for all JPBW outbreaks in this area. Data from additional jack pine stands are needed to validate these predictions. In addition, we have assumed that the relationships between mortality, growth loss, and stand characteristics are linear (i.e., based on linear regression). Other studies suggest that these relationships may be non-linear (e.g., McCullough *et al.* 1996). Continued refinement of these important relationships should give the model more predictive power.

TRIAL SIMULATIONS

Sixty-four trial simulations were run to determine the amount of merchantable volume and present value loss that could be expected in some typical stand types. The stands selected for these trial simulations were various combinations of four initial average stand DBH's, four site index values, four initial stand densities, and two simulation lengths. All trial simulations used a price of $20 per cord for jack pine pulpwood and a discount rate of 4 percent. On average these trial simulation stands experienced three JPBW outbreaks over the course of the simulation. Results of these trial simulations ranged from 5.9 to 49.7 percent loss in merchantable volume and from $3 to $103 per acre present value loss. The mean percent loss in merchantable volume and present value was 31.3 percent and $40 per acre, respectively.

During the trial simulations, it was observed that the average DBH of the trees in the outbreak stand was greater than the average DBH of the trees in the non-outbreak stand at the end of the simulation. This pattern is due to the assumption that diameter growth is inversely related to stand density. The outbreak stand suffers increased tree mortality during periodic outbreaks. Thus, outbreaks act as thinnings that reduce stand density and increase diameter growth. Between-outbreak diameter growth in the outbreak stand more than offsets diameter growth reductions that occur during the outbreaks. As a result, tree mortality is a more important factor affecting volume and economic loss than growth loss.

CONCLUSIONS AND FUTURE DEVELOPMENT

Annually, forest pests, such as the JPBW, play an important role in determining stand composition and timber supply. Forest managers need special tools to help them predict the effects insects will have on future timber supply and to help them develop management plans that reduce the future occurrence and severity of damage from insect attacks (MacLean and Porter 1996).

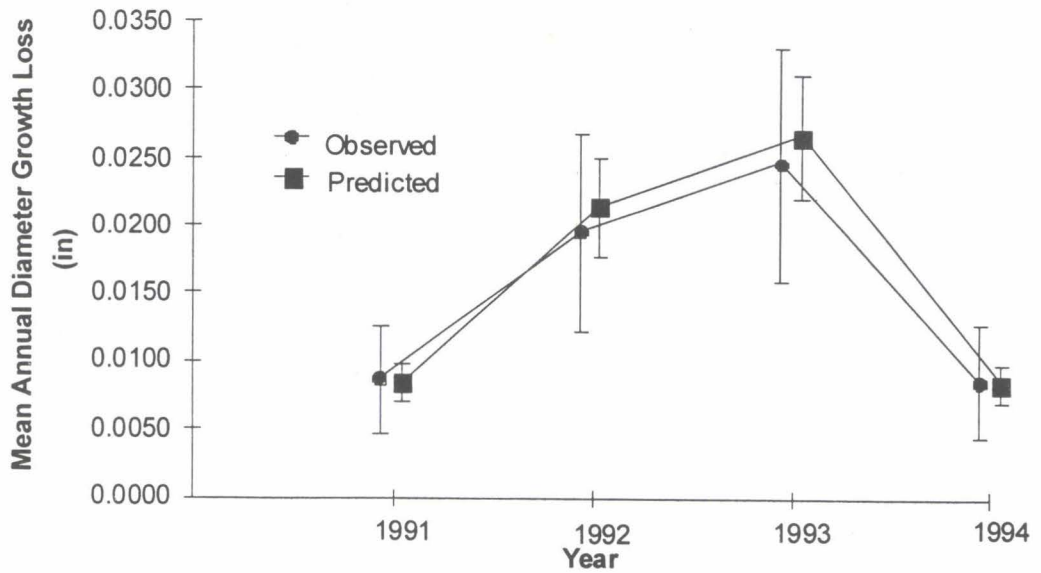

Figure 5.—*Predicted and observed mean diameter growth loss with 95 percent confidence intervals.*

These tools include decision support systems (DSS). A DSS is a computer software system that incorporates forest inventory data and models of pest activity and impact (MacLean and Porter 1996). A DSS is typically designed to improve the current situation of the forest manager by aiding in the decision-making and justification process (Marshall and McCullough 1995). Important questions about management strategies and resource allocation can often be answered more efficiently with the help of decision support systems.

Forest pest impact models, such as the one described above, are important components of decision support systems. However, the model described above is only the first step toward the development of such a tool. Continued improvement of the mortality and growth loss relationships is essential. In addition, data from other areas in Michigan and the Lake States region are needed to validate these relationships. This stand-level model should be transformed into a forest-level model by applying it to a number of stands simultaneously. This, along with incorporation of geographic information systems (GIS), could be accomplished by programming the model in a different development environment such as ArcView's Avenue™[5] programming language (ESRI, Redlands, CA) or a conventional language such as C++.

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DAILY AIRTANKER DEPLOYMENT WITH INTERACTING BASES

Kazi Saiful Islam and David L. Martell[1]

ABSTRACT.—Each day regional fire duty officers must decide how many airtankers to acquire and where to deploy them to minimize initial attack response time. We consider the case of fire arrival rates that vary over the day and several bases with overlapping attack zones. We describe how we extended Larson's steady state hypercube queueing model to account for constraints on airtanker strike range and time-dependent system behavior and how our model can be used for daily airtanker deployment planning in the province of Ontario.

INTRODUCTION

Fire plays a significant role in many Canadian forest ecosystems and an average of 1,847 fires burned an average of 22,710 km^2 per year in the province of Ontario during 1976-1988 (Martell 1994). The Ontario Ministry of Natural Resources (OMNR), the agency responsible for forest fire management in Ontario, spends roughly $35 million on the basic fixed cost of its fire management organization and an average of approximately $35 million on Emergency Fire Fighting (EFF) each year. From a national perspective, Canadian forest fire management agencies spend a combined total of roughly $288 million per year.

Airtankers play a very significant role in forest fire management in Canada and in this paper we describe our development of a decision support system that can be used to help decide where to deploy airtankers each day so as to minimize their initial attack response time. We begin by describing the daily airtanker deployment problem and some of the earlier research on the subject. We then present our daily airtanker deployment model and some preliminary results of its application to a small test problem. We conclude with a brief discussion of our future research and implementation plans.

THE INITIAL ATTACK SYSTEM

The OMNR's initial attack system objective is to contain fires while they are small and thus limit the spread and damage they cause. The boreal forest region of Ontario, the portion of the province in which most fire activity takes place, is blessed with an abundance of water in small ponds and streams, and lakes from which amphibious airtankers can pick up water. Fires are placed in the initial attack queue as they are reported and fire suppression resources are dispatched as soon as they become available. Initial attack crews usually travel to fires by helicopter or truck, set portable power pumps at water sources near the fire, lay hose up to the fire, and establish a hose line around the fire as quickly as possible. Large amphibious airtankers based at airports fly out to the fire area, skim low over the surface of a nearby lake, scoop water into their onboard tanks, and drop that water on the fire. The cruising speed of airtankers is such that they usually arrive at the fire and drop several loads before the initial attack crew arrives at the fire site ready to begin their control action on the ground. Airtankers can therefore attack relatively small fires for fire crews and increase the likelihood they will be controlled at a small size.

THE DAILY AIRTANKER DEPLOYMENT PROBLEM

The OMNR owns 9 CL-215 airtankers and can borrow additional airtankers from other agencies to satisfy the increased demand that arises during "fire flaps" when many fires arrive during short intervals of time and threaten to overwhelm the initial attack system. Each day fire managers must decide how to deploy the available airtankers at initial attack bases across the province. They attempt to deploy the airtankers close to areas where fires are expected to occur and thereby reduce initial attack response times. Our objective is to develop an airtanker deployment model that fire managers can use to help resolve daily airtanker deployment decisions.

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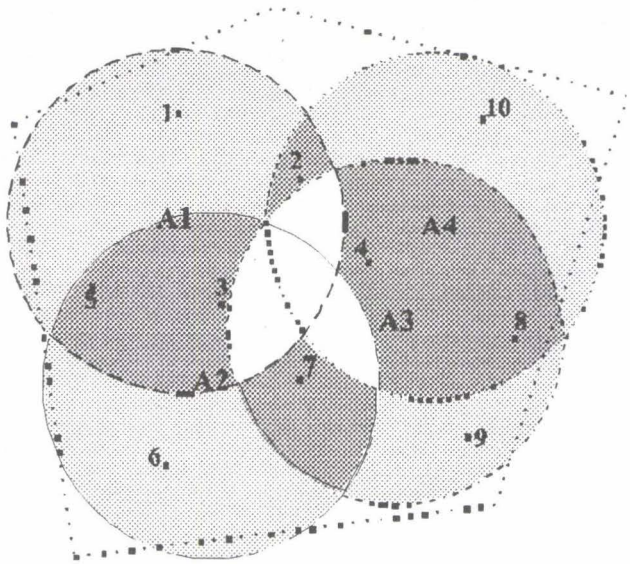

Figure 1.—*Airtanker bases, initial attack strike range boundaries and fire nodes. The airtanker bases are nodes A1, A2, A3, and A4 and the fire nodes are nodes 1, 2, ..., 10. Some fires may lie within range of one or more airtankers while others may not be covered by any airtankers.*

The initial attack airtanker system can be viewed as a spatially distributed queueing system with fires as customers and airtankers as servers. One important distinguishing feature of the initial attack system is the fact that unlike many queueing systems in which customers arrive at stationary servers, airtankers travel to their customers. The fire arrival process is a non-homogeneous Poisson process and airtanker service times are long relative to the diurnal variation in the fire arrival rate. Since the system never really reaches steady state it is not reasonable to partition the day into a small number of time intervals and predict the steady state performance of the system during each interval as is commonly done in urban emergency response system planning.

Daily fire occurrence can be modeled as a time-dependent Poisson process with the fire arrival rate determined by current and past weather in each area. The OMNR partitions the province of Ontario into many small independent sectors and uses historical fire weather and fire occurrence data to predict daily fire occurrence by sector expressed in terms of the expected number of fires per day. Historical fire report time data is then used to model time-dependent fire arrival rates throughout the day. Let $f(t)$ denote the probability distribution of the arrival time of fires in a particular sector. If the expected number of fires arriving in that sector during the day is λ_{Day}, then λ_t, the fire arrival rate at time t can be expressed as $\lambda_t = f(t)\,\lambda_{Day}$.

Airtanker service time includes the time required to fly to and from the fire as well as the on-scene fire fighting time. It is reasonable to assume the on-scene fire fighting time is exponentially distributed and that it varies by daily weather and forest vegetation, which vary by sector. Since the service time includes both the on-scene fire fighting time plus the two-way travel time it clearly cannot be exponential, but later we describe a heuristic calibration procedure that makes it possible to approximate system behavior by assuming the service time is exponential with calibrated parameters that are based on both the travel and on-scene fire fighting times.

PREVIOUS RESEARCH

Fortin (1989) studied amphibious airtanker operations in the province of Quebec, which owned 21 airtankers during the 1980's. She analyzed Quebec's historical airtanker data and found that an Erlang distribution could be used to model airtanker service time—the travel time plus on-scene fire fighting time. Given the large number of airtankers relative to the fire load she modeled Quebec's airtanker system as an $M(t)/E_k/\infty$ queueing system. The OMNR has a larger initial attack fire load than Quebec so its 9 airtanker fleet size renders the infinite server assumption inappropriate for Ontario.

Martell and Tithecott (1991) partitioned the Northwest region of Ontario into 4 sectors, each of which enveloped a single airtanker base, and modeled initial attack airtanker operations in each sector as an independent queueing system. The duty officer provided daily subjective assessments of the expected number of people and lightning caused fires in each zone by subjectively modifying predictions produced by statistical models and they solved the M(t)/M/s queueing system equations numerically for each zone independently. The results were then presented to the fire managers in the form of computer-generated graphs. The fire managers involved expressed concern that the model did not capture the important interaction between airtanker bases.

Larson (1974) developed the hypercube queueing model (HQM) which models the interaction of distinguishable servers in a spatially distributed queueing system. The HQM is a descriptive model that provides steady state probabilities of the system states and many related performance measures given the airtanker deployment. The model is based on an M/M/*s* queueing system with distinguishable servers, but airtanker service time has a general distribution since it includes a very significant travel time component in addition to the on-scene fire fighting time. The HQM model assumes airtankers have sufficient fuel capacity to cover any, including the most remote, fire in the region.

The HQM is a steady state model and its application to a system in which fire arrival rates vary over time is contingent on the assumption that one can partition the day into discrete time intervals and use the HQM to produce steady state results for each such interval. In the case of airtankers fighting forest fires, peak congestion follows the peak fire arrival rate and system performance deteriorates. When the system becomes congested the best HQM performance is achieved by moving all airtankers to a centrally located base. Urban fire trucks can "gas up" on the way to a fire, but airtankers operate in remote areas and since they can seldom refuel en route to or from a fire, they have a maximum strike range beyond which they cannot fly, so the use of a single central base would leave many fires "uncovered" by an airtanker.

Table 1 illustrates the more significant differences between the HQM and an airtanker system. Given these discrepancies, we decided to extend the HQM by restricting airtankers to designated strike ranges and modeling the time-dependent behavior of the system.

A DAILY AIRTANKER DEPLOYMENT MODEL

Our daily airtanker deployment model is an extension of Larson's (1974) basic HQM developed by introducing: (1) time-dependent fire arrival rates and (2) constraints on the initial attack range of airtankers. The service time includes an on-scene component and a travel-time component that depend upon estimates of the probabilities that each airtanker is dispatched to a fire at each fire node. The model provides transient system state probabilities and many related performance measures such as the virtual response time to a fire that arrives in the system at time t given the airtanker deployment. We then extended a heuristic developed by Berman *et al.* (1987) to find "good" locations for s airtankers for a specified deployment time interval.

Heuristic to Solve the Daily Airtanker Deployment Problem

We deal with a fire region that contains several airports (nodes G_A) and a large set of potential fire locations (nodes G_F) where fires may occur. The daily airtanker deployment problem is a very complex continuous time stochastic control problem with control variables that indicate which airport each airtanker should proceed to after it completes the on-scene service of each fire. That problem is beyond the scope of our current analysis, and we deal with a much simpler problem that entails deciding where to base each airtanker for some specified time interval which we refer to as the deployment time interval. We assume each time an airtanker completes serving a fire it returns to the airport at which it was deployed at the start of the deployment time interval. It cannot be deployed at some other airport nor can it be dispatched on a multiple fire sortie that might take it to more than one fire before it returns to its base. The deployment time interval will be some time interval less than or equal to the entire day. We envisage duty officers initially selecting a deployment interval that begins at the start of a day and extends to the mid-point or the end of the day, and then selecting new deployment intervals that begin after the duty officer has observed the system and decided he or she wishes to revise the deployment on a rolling planning horizon basis.

Let $X = (X^1, X^2, ..., X^s)$ denote the locations (airports) where the s airtankers are deployed at the start of the deployment time interval. Assume airtanker I is constrained to an initial attack radius a_i specified by the duty officer. An airtanker certainly cannot fly beyond the range imposed by its fuel tank capacity but its actual range is flexible as the duty officer can make a trade off between the amount of fuel loaded into the tank, the flying distance to the fire and the amount of flying time devoted to cycling between a landable lake close to the fire and dropping water on the fire. Duty officers assess regional fire loads and tend to limit the initial attack radius and concentrate their airtanker resources on high priority areas as anticipated fire loads increase so they are not "caught short" with all airtankers far from their bases when a high priority fire is reported. The initial attack strike range is therefore a decision variable that must be less than or equal to the maximum physical distance imposed by the fuel tank capacity and our model is designed to allow duty officers to evaluate the initial attack radius as well as the deployment base for each airtanker.

Table 1.—*Comparison of the hypercube queueing model and an airtanker system*

Larson's HQM	Airtanker System
Distinguishable servers	Distinguishable servers
One initial attack queue	One queue for each airtanker
No limit on strike range	Constrained attack radius
Exponential service time (needs to be calibrated)	Exponential service time (needs to be calibrated)
Constant arrival rate	Time-dependent arrival rate
Steady state solution	Time-dependent solution

Airtanker initial attack zones may overlap. Let N_i denote the set of potential fire locations (nodes) "covered" by airtanker i (within radius a_i). Therefore $N_i \equiv \{[j] \mid d(X^i, j) \leq a_i, \forall j \in G_F\}$. Let $\bar{S}_i(X^i)$ denote the mean service time of airtanker i deployed at base X^i. Since we assume airtankers always return to their bases between fires it includes the fire suppression time plus two-way travel time.

$$\bar{S}_i(X^i) = \sum_{j \in N_i} \bar{w}_{ij} \left(\bar{U}_{ij} + \frac{2}{v_i} d(X^i, j) \right) \quad \text{for } i = 1, \ldots, s$$

where U_{ij} is the average fire suppression time for airtanker i fighting a fire at node j and $\bar{w}_{ij}$ is the probability (averaged over the deployment interval) that the next fire that starts at node $j \in N_i$ will be assigned to airtanker i.

Our dispatch strategy is as follows. As soon as a fire is reported, the nearest available (idle) airtanker that covers that node will be dispatched to that fire, but if no covering airtankers are available, the fire is assigned to the queueing subsystem of the covering airtanker that has the shortest queue length and is served by that airtanker on a FCFS basis. The behavior of the system is described by a set of difference equations representing an M(t)/M/s system with distinguishable servers that can be solved numerically. Our state variable is an $s+1$ dimensional vector with the first element denoting the number of fires in the system. The next s elements are the number of fires in each airtanker's queueing subsystem. Table 2 shows the first 42 possible system states. State 17, for example, has 3 fires in the system. One is being served by airtanker 2, a second is waiting in airtanker 2's queue, and the third fire is being served by airtanker 3; airtanker 1 is idle.

Let $E[R_{X,t}]$ denote the expected virtual response time at time t, $E[W^{(q)}_{X,t}]$ the expected virtual waiting time in the initial attack queue at time t, and $E[T_{X,t}]$ the expected travel time to a fire that arrives in the system at time t. Then $E[R_{X,t}] = E[W^{(q)}_{X,t}] + E[T_{X,t}]$. Let $AR_X(\Delta)$ denote the average over the deployment time interval $\Delta \equiv [\Delta_L, \Delta_U]$ of $E[R_{X,t}]$, the expected virtual response time. Then $AR_X(\Delta) = \frac{1}{\Delta} \int_{\Delta_L}^{\Delta_U} E[R_{X,t}]\, dt$.

Our objective is to identify a location vector X^* in the fire region that will minimize $AR_X(\Delta)$.

The Mean Service Time Calibration

The airtanker service time includes the time to fly to and from the fire plus the on site service time. Since the flying time to a fire depends upon the deployment strategy, the service time we use to identify a good deployment strategy is an endogenous variable that depends upon the deployment strategy. We modified the

Table 2.—*The first 42 states if the M(t)/M(s) system with distinguishable servers*

State index	State symbol
0	0:000
1	1:100
2	1:010
3	1:001
4	2:200
5	2:110
6	2:101
7	2:020
8	2:011
9	2:002
10	3:300
11	3:210
12	3:201
13	3:120
14	3:111
15	3:102
16	3:030
17	3:021
18	3:012
19	3:003
20	4:400
21	4:310
22	4:301
23	4:220
24	4:211
25	4:202
26	4:130
27	4:121
28	4:112
29	4:103
30	4:040
31	4:031
32	4:022
33	4:013
34	4:004
35	5:500
36	5:410
37	5:401
38	5:320
39	5:311
40	5:302
41	5:230

mean service time calibration suggested by Berman *et al.* (1987) for our airtanker model. The steps are as follows.

Step 0: Estimate the initial mean service time for all airtankers based on a simple assumption concerning the assignment of fires to airtankers (an airtanker fights all the fires within its attack radius)

Step 1: (i) Run the model using the initial estimate of the mean service time for all airtankers

(ii) Estimate $\bar{w}_{ij}$, the probability (averaged over the deployment interval) that the next fire that arrives at node $j \in N_i$ will be assigned to airtanker i

Step 2: Calculate a revised estimate of the mean service time based on the current estimate of $\bar{w}_{ij}$

Step 3: Calculate e_i, the difference between the initial and revised estimates of the mean service times for all airtankers

Step 4: Stop when e_i is small enough for all i.

The Airtanker Deployment Heuristic

We use the following heuristic procedure to identify a good deployment strategy for the airtankers.

Step 1: i) Choose the deployment time interval
$\Delta \equiv [\Delta_L, \Delta_U]$
ii) Specify an initial airtanker deployment
$X = (X^1, X^2, X^3, \ldots, X^s)$
iii) Set the initial estimate of the average of the expected virtual response time over the deployment interval Δ equal to some large number, $AR^0_X(\Delta) = m$

Step 2: Solve the modified HQM and perform the mean service time calibration to produce

1) calibrated mean service time

b) $\bar{w}_{ij}$, the probability (averaged over the deployment interval) that the next fire that arrives at node $j \in N_i$ will be assigned to airtanker i

Step 3: Evaluate a revised estimate of the average of the expected virtual response time over the deployment time interval, $AR^R_X(\Delta)$

Step 4. If $| AR^R_X(\Delta) - AR^0_X(\Delta) | < \zeta$,
Then
Stop, X is the chosen deployment
Otherwise
Set $AR^0_X(\Delta) = AR^R_X(\Delta)$
GO TO Step 5 to revise the airtanker deployment

Step 5: Myopically revise the location of each airtanker (one at a time) to improve the rate at which it serves the fires that have been assigned to it, and solve the modified HQM again

a) Revised airtanker location
$X_R = (X^1_R, X^2_R, \ldots, X^s_R)$

b) Set $X = X_R$
Return to Step 2 to solve modified HQM and perform the mean service time calibration.

PRELIMINARY RESULTS

We applied our model to the very simple test problem with 3 airtankers and 19 fire nodes illustrated in figure 2 which shows the fire nodes and fire arrival rate at each node. Figure 3 describes the performance of the system for the initial deployment of the 3 airtankers at nodes 1, 3 and 8. The solution is described in table 3, the first column of which shows the initial and interim deployment strategies evaluated at each iteration. The second column contains the time averaged initial attack response time and the third column contains the recommended deployment strategy generated by the deployment revision procedure. We tried two different initial deployment strategies for this test problem. The results presented in table 3 indicate they converge to two different deployment strategies with almost identical performance measures.

FUTURE RESEARCH AND IMPLEMENTATION

We have made many simplifying assumptions in order to develop a tractable model and many aspects of the system merit further investigation. Forest fires grow as they wait in the queue so service time actually depends upon waiting time, but we have ignored that important characteristic of initial attack system. It may well prove unnecessary to account for such behavior on most days but the issues should be investigated to determine the extent to which our assumption is acceptable.

The state space of our model grows very quickly as the number of servers increases. Larson (1975) developed approximation procedures for solving his steady state HQM model. It may prove necessary to develop approximate solution methods for our time-dependent constrained attack range airtanker HQM.

We have used a calibrated exponential service time distribution that merits further investigation. We are

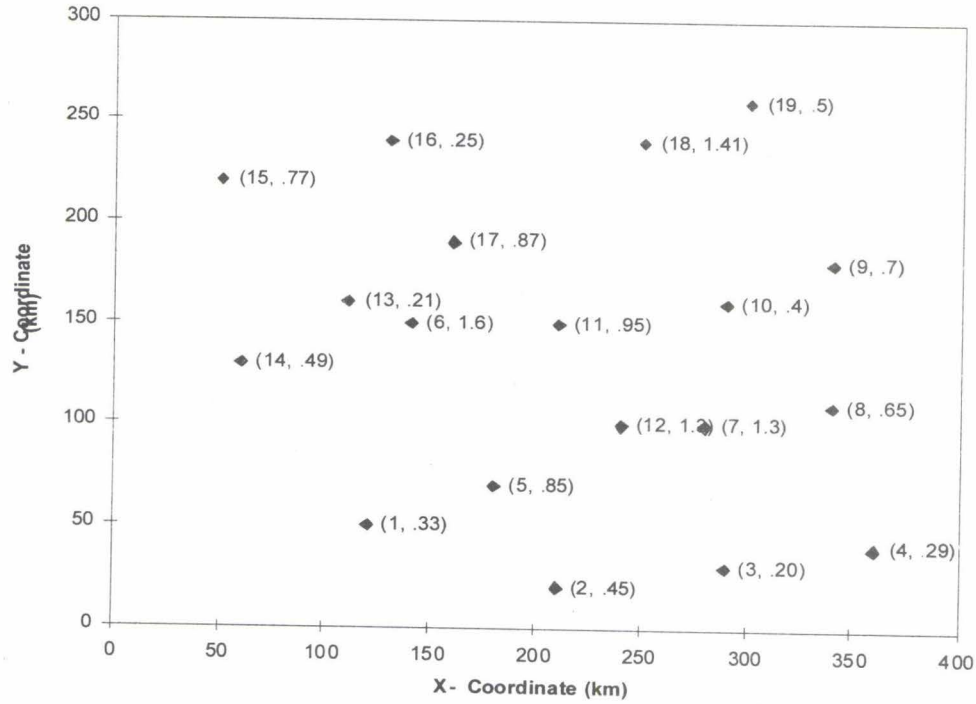

Figure 2.—*Map of fire and airtanker nodes for a small test problem. The first number inside the parentheses is the node number and the second is average fire arrival rate at that node expressed in terms of fires per hour.*

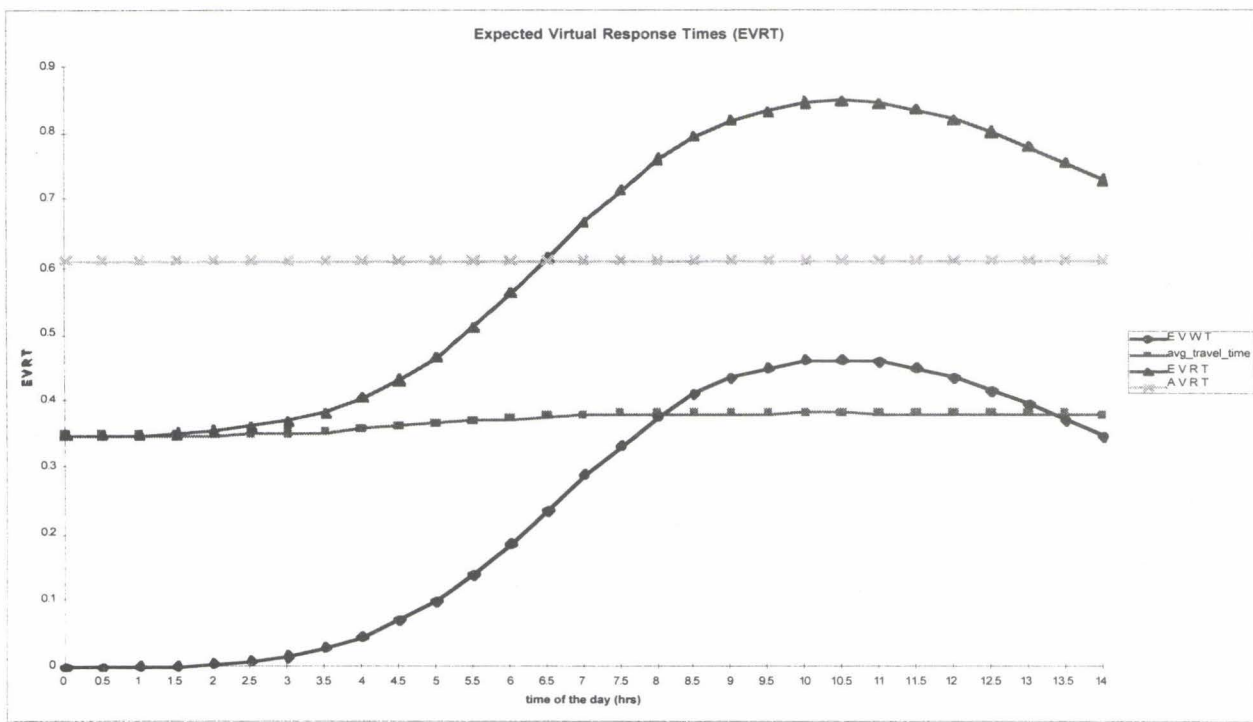

Figure 3.—*Predicted airtanker system performance with airtankers deployed at nodes 1, 3 and 8. EVWT is the expected virtual waiting time, EVRT the expected virtual response time, and AVRT the average over the deployment interval, of the expected virtual response time.*

Table 3.—*Preliminary results with 3 airtankers and 19 fire nodes*

Initial deployment (X^1, X^2, X^3)	$AR_X(\Delta)$	Recommended deployment (X^1, X^2, X^3)
	hours	
1, 3, 8	0.612	15, 6, 12
15, 6, 12	0.525	18, 7, 11
18, 7, 11	0.481	13, 7, 11
13, 7, 11	0.473	13, 7, 11
(Stop)		
3, 9, 19	0.572	6, 8, 18
6, 8, 18	0.472	6, 8, 18
(Stop)		

currently developing a simulation model that can be used to investigate some of these issues and to "validate" our HQM. We also plan to field test our model in Ontario during the 1998 fire season.

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WILDLAND FIRE AND WEATHER INFORMATION DATA WAREHOUSE

Delvin R. Bunton[1]

ABSTRACT.—The USDA Forest Service stores fire occurrence data in a relational data base for planning, analysis, and other purposes. Weather observations are stored in the same data base for all five federal land management agencies and some state wildland agencies. Ready access to fire occurrence and weather data enables managers, planners, and operations personnel to make informed decisions based upon the past and projections into the future. This presentation discusses the design philosophy behind the data base, issues dealing with the care and feeding of the data base and data stored there, and how data helps field users

DATA WAREHOUSE CONCEPTS

Corey and Abbey (1997) define a data warehouse as "a collection of corporate information derived directly from operational systems and some external sources." This definition broadly fits the National Interagency Fire Management Integrated Data base (NIFMID) discussed in this paper. Data warehouses support business decisions, not business operations. When business managers, whether in a corporation or a governmental agency, ask "What if?" questions, the data to answer the business questions will come from a data warehouse of one kind or another.

Operational data bases are crucial to many businesses and government agencies. Operational data bases:

1. Typically handle one record at a time (such as an invoice, weather observation, or fire).
2. Often have predictable busy and slack times during a day, week, or month.
3. Are organized to meet specific business needs.
4. Typically change slowly (if at all) over time, although some changes are abrupt and dramatic.

Data warehouses, in contrast, exhibit different characteristics. They:

1. Typically handle many records at once (all fires in 1994, weather stations in California, etc.)
2. Usage is either high or very low.
3. Are designed to cross business lines.
4. Provide ways to link data that may not be directly related.
5. Work with longer time periods to find trends.
6. Change structure over time to meet new and changing business needs.

Before computers, data warehouses existed as paper files in boxes and cabinets. Many businesses and government agencies still use this data storage method, and it works quite well for many applications. In their analysis of fire occurrence in California national forests, Show and Kotok (1923) extracted data by hand from 10,449 individual fire reports. They summarized data many different ways that required numerous passes through the paper reports. Their findings affected fire planning for several decades, and some findings are still applicable today. One interesting sidelight is the information Show and Kotok used is very similar to what Forest Service fire managers today record about fires (Donoghue 1982).

Barrows (1951) used computer cards for each fire (approximately 36,000) when he analyzed fire occurrence in the northern Rocky Mountains (primarily Montana and northern Idaho). Barrow's ability to quickly search for common denominators among the reports allowed him to gain insights that were hidden from earlier researchers. He presented his findings in many detailed tables and graphs that clearly show characteristics of the fires studied. Many of his findings are still applicable today.

Goldberg and Vijayan (1996) reported that managers at Victoria's Secret (a women's intimate apparel retail chain) found the company was spending too much time and money collecting information and too little time

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analyzing it. When they did analyze their data, they found some surprises. Stores were regularly stocked based on a mathematical average. When stocking levels at each store were based on local customer buying patterns, profits rose. The company put items on sale at many stores simultaneously even when the customers at some stores were willing to purchase the items at full price. Company management changed discounting practices, which again increased profits.

The application of modern data storage and analysis tools enables managers to find insights into relationships masked by data volume, or other trends. Data base tools allow users to quickly summarize data in ways that were possible in past times, but only with great effort. The challenge is to organize the data so those new relationships become visible, and then demonstrate to management that the findings have relevance to their decision-making.

REAL WORLD DATA STORAGE

Early managers submitted fire reports on paper forms through the organizational hierarchy. Copies were usually kept at the Forest and Regional offices. Beginning in 1940, fire reports were keypunched onto computer cards at either the Regional or National offices and stored for analysis. Some Forest Service paper fire reports from before 1970 still exist, but most were regrettably destroyed.

Weather observations were typically stored in paper form at local offices. Some data from before 1972 when AFFIRMS (Administrative Forest Fire Information Retrieval and Management System) began operations still exists. Local offices entered weather observations into AFFIRMS with a computer terminal. Weather forecasters retrieved the data and issued forecasts, which were then sent back to local fire management offices via AFFIRMS.

From 1974 to 1992, the Forest Service stored both fire occurrence and daily weather observations on computer tape at a departmental computer center (Furman 1975, Yancik and Roussopoulos 1982). Users ran a program to find out which tape had the information they wanted, and then ran another program to extract the data. Only one weather data format was defined, and two fire formats (neither of which gave the full data record) for the general user. Users who had special needs generally did not have their data needs met unless they either wrote the extract programs themselves, or found someone who could write the program for them.

Since fire data was added to the tapes only once per year, usually in March or April, additions and corrections were virtually impossible. Many weather observations and some fire reports were never added to the tape files, and so were missing from any analysis. Recent analysis shows most of the missing fires were very large fires that were still active (not declared out) until well after the annual report for the year was completed. Missing weather observations were most often on the first day of a fire since the weather observer was also a firefighter.

In 1986, the fire report system was converted to use a data base for storage. This improved data access to fires that occurred in 1986 and later years. Field offices were finally able to correct recent fire records, and generate custom reports as needed. Units could not correct fires from prior to 1986. Fires were copied annually to the tape files for archival and retrieval purposes.

BUILDING THE FIRE AND WEATHER DATA WAREHOUSE

In 1992, the Department of Agriculture began consolidation of computer services; and eventually closed the computer center that housed the tape files. The Forest Service decided to build a data base to contain both the fire and weather data using a relational data base to provide easier access to the data. The fire and weather portions of the data base were built by separate development teams to speed the transition using the philosophy described below. The overall structure was named the National Interagency Fire Management Integrated Data base (NIFMID). The NIFMID was originally designed around four key principles:

1. Operational weather data would be managed by the Weather Information Management System (WIMS) that was under development at the time. WIMS is an interactive system currently used by all five Federal land management agencies (Forest Service, Bureau of Land Management, National Park Service, Bureau of Indian Affairs, and Fish and Wildlife Service), many states, and some local wildland fire protection agencies.
2. Forest Service fires would continue to be managed by FireStat (USDA Forest Service 1995b) to minimize field disruption. Local Forest Service offices enter fire data on their local computers and then transmit the fire data to NIFMID where the data is loaded and immediately available for analysis purposes. Department of Interior fires are entered and stored on a different computer system.
3. Historical weather and fire data would be readily available to those who need the data.
4. Users could download data for local analysis, or obtain summary reports from both historical and operational data bases.

The NIFMID architecture includes over 50 tables that logically fall into six groups. Where it makes sense,

codes (such as aspect, state, county, etc.) are shared by both fire and weather.

1. Fire occurrence data (information on each fire, including basic information, events, acres burned by ownership, resources used on the fire).
2. Fire code reference tables (fuel model codes, organizations, vegetation codes).
3. Current weather and weather-related tables (up to 24 observations per station per day, forecasts, station location data).
4. Historical weather tables (one observation per station per day).
5. Weather reference tables (fuel models, aspect, wind direction).
6. Common reference tables (states, counties, principle meridians).

Since we chose to blend two operational systems (weather and fire reporting) within a data warehouse, there were two problems to face. The first was to migrate historical data into the data warehouse and provide easy user access to the data. The second was to create software to capture and validate new data such as fire reports, weather observations, and forecasts.

LOADING THE WAREHOUSE WITH HISTORICAL DATA

An empty warehouse does not attract many customers (unless you are selling warehouses). An important value from the warehouse concept was the ability to easily compare past years against current years to estimate workload and possible trends.

Before NIFMID was created, the Forest Service had automated fire data records from 1970-1992 stored on tape. There were also 8 years of data (1986-1992) in a data base (the data records on tape for 1986 and later were derived from that data base). The data was extracted from tape and loaded into flat files on the target computer. A custom loader program read the data from the flat files and populated the several tables that contain fire data. Some of the initial loads failed when non-standard data was discovered in some fields. After those problems were repaired the data loaded properly. Approximately 280,000 fires were loaded using this procedure.

The weather loading process was similar to the fire process. Data was extracted from tapes and loaded using Oracle[2] SQL*Loader. Approximately 15 million weather records were loaded by this method.

[2] *The use of trade or firm names in this article is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.*

Once the historical fire and weather data was loaded, the data was indexed to speed retrieval queries. Fires were indexed by report unit, year, and fire number. Weather observations were indexed by station number and observation date. Data properly indexed can be retrieved very quickly, but queries that scan for unindexed values must read the entire table to find the target records.

Numerous data problems were found as users worked with the data. Errors will undoubtedly surface for several more years. Data shifts in the old data (everything one column off) are the hardest to find and fix. When users find an error, they should have the ability to fix the error. This feature is not entirely automated, although errors do get corrected. Some records that appear to be errors (for example, a fire over-wintering under snow) may be correct.

Some of the more interesting errors and anomalies, almost all from pre-data base days, included the following:

1. Some large fires were never input to the fire occurrence data base, so summaries did not add to the correct number of fires nor acres burned. Missing fires were added to the data base as we discovered their absence.
2. Some fires were entered two or more times and not removed from the data base. This was a known but difficult to fix problem until the fires were in a data base. Most of these duplicates were deleted.
3. Fire report rules at the time required each Forest that had part of a large fire to enter their portion of the acres burned (fairly rare event). In one year when numerous fires burned on several Forests, the error in double counted acres exceeded the average annual burned acres. This was quickly corrected.
4. About 1 percent of the fires located by latitude and longitude plotted outside the state of origin. Most of these problems were quickly found and fixed.
5. The most likely day a weather observation was missing from the observation file is the first day of a large fire on the management unit.
6. Weather observations were stored with dry bulb temperature and relative humidity. However, some observations prior to 1973 were entered with either wet bulb or dew point in the relative humidity field. The detection is more complex than the repairs, which are underway now.
7. Trace precipitation under AFFIRMS use "T" to note that there was less than 0.01" of precipitation. All "T" values were changed to 0.005" precipitation so mathematical totals became possible.
8. The weather loader program stored zero percent relative humidity for days with no observed relative humidity. When users analyzed the data, the analysis programs showed many very dry days.

Since zero humidity is very unlikely, all those values were changed to null—meaning the value is missing.

FEEDING THE WAREHOUSE (OPERATIONS)

Properly feeding a data base is critical for success. Clean data is essential; there must be methods in place to enforce data integrity. Direct input without data base procedures almost guarantees errors will creep into the data.

The FireStat application operates at each Forest and some District fire offices. Fire managers enter data on up to six screens about each fire. Some fields are range checked at input time. When the manager is ready to transmit the fire to NIFMID, each fire is rigorously checked again using national and local data ranges. Values that are acceptable nationally may not be within valid ranges for a specific state. For example, fires above 11,245 feet elevation would be accepted in Colorado but not in Oregon. Fires with one or more serious errors are rejected, and must be corrected before FireStat will transmit the fire to NIFMID.

When the fire reaches NIFMID, it is checked again and a unique fire number is assigned. As soon as a fire is successfully loaded in NIFMID, any user can access the fire in reports, summaries, or download portions of the fire for analysis.

Catching errors before a fire is sent to NIFMID is much less expensive (and more accurate) than correcting fires loaded into NIFMID with errors. The effort to find and correct errors is significant, especially for fires prior to the current year.

Several data loading processes are implemented for WIMS. Field users can input weather observations directly into WIMS and immediately use the data for analysis and summaries. This is the typical path for manual stations or stations that have no automated link to WIMS. Users can also send the system administrator a data file to load. Over half of active weather stations (out of about 1,680 active stations) are now Remote Automated Weather Stations (RAWS). Observations are taken hourly and transmitted periodically to a collection and processing facility. The processing facility reformats the data for transmission into WIMS, and WIMS loads the data into the appropriate tables.

WIMS grows daily with ingestion of weather observations and forecasts for the active stations, many of which record data year around, 24 times per day. Approximately one year of data is kept on line.

USING DATA FROM THE WAREHOUSE

Many users access and retrieve data from NIFMID, The most common usage supports fire planning work using the National Fire Management Analysis System (NFMAS) to model and plan for wildland fire suppression needs. The process relies heavily on historic fire occurrence and weather observation data to model local fire behavior and growth parameters.

KCFast (USDA Forest Service 1995a) was developed to take user input and build a batch query that is sent to NIFMID for processing. Users can request fire or weather data or summary reports without learning a complex computer control language. Output from KCFast gives users a window into NIFMID. Output generally falls into one of three categories.

1. Data files for input into analysis programs such as NFMAS, FirDat, and Season (weather analysis tools), Fires (a program that allows comparison between weather and fire occurrences), RERAP (Rare Event Risk Assessment Process), and custom analysis tools such as local data bases and spreadsheets. Fire planners find many of the errors since they must review each fire during the preliminary planning process.
2. Standard reports such as weather forecasts, fire inventories, weather observation inventories, weather station lists, etc.
3. Predefined reports with user input to list or summarize fire data for the geographical area desired. Currently there are over 150 reports for fires, and a few weather summary reports.

The third output type allows managers to request summaries of various types. One recent example was, "How much would it cost the Forest Service if power transmission line owners were not held responsible for fires caused by downed powerlines?" Another requester asked for the 20 most expensive fires within the last 10 years. This type of output is very flexible and allows local managers great flexibility to answer questions and analyze their data.

FUTURE

There are ongoing discussions about other kinds of data that might be stored with the fire and weather data. One likely addition is data on management-ignited prescribed fire on Forest Service lands. At present the Forest Service does not keep such records on a national basis. Another possibility is aircraft usage, although that is less certain.

A new tool that is only a concept at this time will allow local fire managers to download fire and weather data for their management area. Once the data is loaded on their microcomputer, a wide range of tools are envisioned to enable the manager to review, correct, and analyze weather and fires. Most wildland weather analysis software only allows users to work with a single weather station. The new software will allow analysis of station aggregates with weighting factors and compare that weather data against their fire load.

Another initiative that will affect NIFMID is the National Interagency Fire Statistics Information Project (NIFSIP). This project is reviewing what data the five federal land management agencies collect with the charter to standardize federal fire occurrence data collection.

Work is ongoing to determine the feasibility of using an Internet web page as the user interface for data requests (such as KCFast now does), and development of data drill-down tools that allow users to do sophisticated data searches.

LESSONS LEARNED

1. Build procedures at the data base level to ensure all records added to the data base meet at least minimal standards. For example, fires at elevations above 14,494 feet (elevation of Mt. Whitney in California) in the lower 48 states would be in error.
2. Scrub your data! Search for and correct obvious errors such as latitudes greater than 90 degrees, or fires that plot in the Atlantic or Pacific Oceans.
3. Check the data as thoroughly as possible at time of capture to identify data problems early. Once the input person leaves the record, corrections are much more expensive.
4. Work closely with interested parties. Sometimes the most off-beat suggestion is popular with the field users when implemented properly.
5. Be flexible. All the uses for the data haven't been invented yet.
6. If you don't use your data, the lowest acceptable accuracy becomes the norm.
7. When data isn't used, user confidence in the data is fairly low. The data may be correct but few believe it to be correct.
8. Sir Josiah Stamp[3] cautioned his peers with a statement that is still true today. He stated, "The government is very keen on amassing statistics. They collect them, add them, raise them to the N^{th} power, take the cube root and prepare wonderful diagrams. But you must never forget that every one of these figures comes in the first instance from the village watchman, who just puts down what he damn pleases". The dispatcher who fills out the fire report probably didn't get to smell the smoke; they do the best they can with the information available to get the report right. The dispatcher or field person is like the village watchman when it comes to fire reports.
9. One last caution: before you rely heavily on data for analysis, try to understand why the data was collected, and the data collection rules. For example, if fire cost per acre is calculated from NIFMID, the analyst should understand that only Forest Service costs are included in the total cost. The true cost may be much higher when costs other agencies accrue are included.

[3] *Sir Josiah Stamp worked for the Inland Revenue Department in England from 1896-1919.*

SUMMARY

The data warehouse provides a way to summarize and analyze fire and weather information for a variety of purposes. Building a data warehouse isn't easy, but when done well, is worth more than the cost. A well-designed data warehouse should allow diverse and seemingly unrelated data to be linked so that interactions and hidden relationships become visible. Many questions can be answered with accessible data.

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MULTIMARKET COMPETITION FOR YELLOW POPLAR TREES IN EASTERN KENTUCKY

G. Keith Hilpp and Matthew H. Pelkki[1]

ABSTRACT.—Merchandising of tree stems can greatly increase profits for timber stands. In eastern Kentucky, the sawtimber, plywood peeler, and fiberstrand markets currently utilize yellow poplar trees. An economic analysis showed some general trends for the yellow poplar market in eastern Kentucky. Markets were found to be highly diameter-specific and each market out-competed the others within a specific range of diameters. However, an increase in the price of one market greatly affected the dominance range of the other markets. This analysis also showed that merchandising of yellow poplar stands provided an increase of 29.2 percent in delivered mill price over the next best single market option.

INTRODUCTION

Timber stand and tree merchandising determines the economic returns and profitability of a timber stand containing tree species utilized by multiple markets (Greber and Smith 1986, Sibal *et al.* 1984). Proper merchandising can maximize economic returns from a stand. In eastern Kentucky, yellow poplar (*Liriodendron tulipifera*) is currently being utilized by sawtimber, plywood peeler, and fiberstrand (also know as engineered wood product or laminated strand lumber) markets. The fiberstrand and plywood peeler markets are both new to Kentucky and have projected demands of 37 thousand board feet (MBF) and 600,000 tons of yellow poplar, respectively (Lowe 1995).[2] The recent establishment of these yellow poplar consumers in 1988, along with the demand for sawtimber, allows for the possibility of maximizing harvest profits through the merchandising of yellow poplar stands.

The objective of merchandising a timber stand is to determine the proper allocation of tree stems to product markets to maximize economic returns. Optimum merchandising is based largely on market conditions and product specifications (Greber and Smith 1986). The goal of this research is to provide insight on the current market state of yellow poplar in eastern Kentucky to better facilitate yellow poplar timber stand and individual tree merchandising.

METHODS

To accurately provide market trends for yellow poplar trees, analysis was completed by 1-inch (in.) diameter classes. The analysis used cubic-foot (ft^3) volume equations for individual yellow poplar trees provided by Hilpp (1997) (table 1). The authors calculated ft^3 volumes by diameter class for each product class (sawtimber, plywood peeler, and fiberstrand). An average tree grade per diameter class was found for yellow poplar trees in Kentucky (table 2) with the use of the U.S. Forest Service's Forest Inventory and Analysis Database (Hansen *et al.* 1992). Listed in table 2, the authors used this value for the tree-grade variable in the volume equations. Because many purchase sawtimber and plywood peeler logs by volumes attained from inside bark scaling diameters, inside bark volume equations were used for these products. However, fiberstrand material is purchased by weight with the bark attached to the stem. Therefore, the authors used the outside bark volume equation for fiberstrand.

To provide volumetric units consistent with prices obtained for sawtimber and plywood peeler, the authors converted ft^3 units into Doyle board-foot units. Table 2 lists an average ratio of International 1/4 in. board-foot to ft^3 volume for each diameter class, which was calculated from Beck (1964). Next, the authors used linear regression to form an equation that would predict the ratio of Doyle board-foot volume to International 1/4 in. board-foot volume by diameter class. The resulting equation

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[2] *Lowe, Larry. 1995. Roundwood consumption in and around Kentucky. Unpublished memo. Frankfort, KY: Kentucky Division of Forestry.*

had a coefficient of determination, or r^2 value, of 0.9875. Table 2 lists the predicted ratios made by this linear regression. With the use of these conversions, Doyle board-foot units were estimated.

Fiberstrand raw material is purchased by tonnage. Therefore, it was necessary to convert ft^3 volume to tons for this product. The authors used a conversion reported in TimberMart South (1996). This publication provides a conversion of 5,800 pounds per standard cord (128 ft^3) which equated to 0.02265625 ft^3/ton for hardwood pulpwood. The authors estimated tonnage units with this conversion.

To examine the effects of price fluctuation and difference in values by log grade, different levels of delivered raw material prices were used. Three levels of sawtimber prices—$350, $225, and $125 per MBF for grades 1, 2, and 3, respectively—reflected the three merchantable saw log grades because purchase prices for saw logs increase with increases in log grade. Reported price lists do not exist for Kentucky (Lowe 1997),[3] so the authors used average delivered log prices in eastern Tennessee. They assumed that eastern Tennessee reported price list reflected eastern Kentucky prices because of similar topography, stand development, and market demand.

[3] *Lowe, Larry. 1997. Log price reporting. Unpublished memo. Frankfort, KY: Kentucky Division of Forestry.*

Table 1.—*Coefficient values for ft^3 volume equations for individual yellow poplar trees for sawtimber, plywood peeler, and fiberstrand product markets (Hilpp 1997)*

Product class	Intercept	d.b.h.	d.b.h.^{2}	Tree grade[a]
Sawtimber[b]	47.73568	-4.20819	0.30533	-8.67475
Plywood peeler[b]	18.13984	0.00000	0.13898	-7.39586
Fiberstrand[c]	19.93393	0.00000	0.24460	-6.76835

d.b.h. = diameter breast height

[a] Below grade trees (USFS grades 4 and 5) are given a value of 4.
[b] Volumes are inside bark.
[c] Volumes are outside bark.

Table 2.—*Values by diameter class for average tree grade, average ratio of International 1/4-in. board-foot volume to ft^3 volume, and predicted ratio of International 1/4-in. board-foot volume to Doyle board-foot volume used in this analysis*

D-class	Avg. tree grade	Ratio Int'l.	Ratio Doyle-Int'l[a]
		cubic feet	
11	3.352466	4.416667	0.470272
12	3.283253	4.510833	0.524194
13	3.039486	4.672857	0.574082
14	2.957698	4.763571	0.619936
15	2.961372	4.898462	0.661756
16	2.669524	4.986154	0.699542
17	2.510498	5.073846	0.733294
18	2.253076	5.241667	0.763012
19	2.324828	5.338462	0.788696
20	2.335356	5.425455	0.810346
21	1.967782	5.537778	0.827962
22	2.246447	5.611111	0.841544
23	2.503691	5.697500	0.851092

[a] Result of linear regression: RATIO = -0.389114 + 0.100313*DBH + -0.002017*DBH2

Hilpp (1997) found that 71.09 percent of yellow poplar plywood peeler logs were of medium grade. To facilitate this analysis, the authors assumed that yellow poplar plywood peeler logs are all of consistent medium grade—arguably the advantage of the plywood peeler market. Therefore, they used only one price, $240/MBF, to determine plywood peeler value.

Two prices were used to determine the value of fiberstrand trees, $17/ton and $25/ton. These prices show the effects of a range in purchase price due to market fluctuation, a predicted increase in unit purchase price, and/or variable radius or distance-dependent purchase pricing.

A key aspect of this analysis is that the multimarket comparisons are on a tree-by-tree basis. The volumes and dollar values listed are those for all the merchantable logs within that tree, i.e., total tree volume and value. To simplify the analysis, the authors did not separate into logs and merchandize them as such. The values listed by diameter class assume that the logs within each tree are of uniform grade (reflected by the graded prices) for sawtimber and plywood peeler. Merchandising is done among trees in this analysis, not among logs within trees.

RESULTS

Table 3 lists estimated Doyle sawtimber and plywood peeler board-foot volumes and fiberstrand tonnage values. Table 4 records values for each tree by diameter class, product class, and associated unit price. A theoretical range of sawtimber prices is identified in table 4 as the "likely" price range. The authors assumed that these prices best reflected market prices by diameter class for sawtimber trees given the average tree grade listed in table 4. The price range for fiberstrand, as reflected by two price levels, demonstrates how a change in unit price affects the competitiveness of the "grade-free" fiberstrand market with the sawtimber and plywood peeler markets.

This analysis makes two separate comparisons. The first comparison examines the sawtimber market in the "likely" price range, the plywood peeler market at a constant price of $240/MBF, and the fiberstrand market at $17/ton. The second comparison differs only by using the $25/ton price for fiberstrand. Bold type and asterisks note the highest price values per diameter class for the first and second comparisons, respectively.

The first comparison shows that each product market can out-compete the other markets within a certain diameter range. For diameter classes 11 through 14, highest values for individual trees are obtained through the fiberstrand market. The plywood peeler market provides the highest value for individual trees within the 15- and 16-in. diameter range. This market also nearly out-competes the sawtimber market grade 2 price within the 17-in. diameter class. The sawtimber market provides the highest values for trees falling within the diameter classes of 18 in. or greater.

The second comparison eliminates the plywood peeler market from the other competitive markets. When the fiberstrand unit price increases, this product provides the highest value in the 17-in. diameter class as well as the 18-in. diameter class when compared to grade 2 sawtimber prices. Above 18 in. in diameter, the sawtimber market continues to provide the highest individual tree value.

Table 3.—*Predicted individual tree sawtimber and plywood peeler board-foot volumes and fiberstrand tonnage*

D-class	Sawtimber	Plywood peeler	Fiberstrand
	- - - - - - - - board feet - - - - - - -		tons
11	19.33	21.11	0.6081
12	30.09	32.80	0.7462
13	48.99	51.37	0.9221
14	67.95	69.41	1.0843
15	89.54	89.17	1.2444
16	123.52	118.51	1.4609
17	158.72	147.85	1.6682
18	205.45	186.00	1.9016
19	243.52	215.23	2.0957
20	287.73	248.23	2.3102
21	352.79	297.46	2.5938
22	394.04	324.83	2.7893
23	440.05	354.68	2.9993

Table 4.—*Dollar values of yellow poplar trees by diameter class for three product markets and associated unit price levels*[a]

D-class	Average Tree Grade	Grade 3 Swtmbr. $125	Grade 2 Swtmbr. $225	Grade 1 Swtmbr. $350	Med.Gr. Plywood $240	Low-end Fbrstrd. $17/ton	Hi-end Fbrstrd. $25/ton
11	3.3525	2.24	4.35	6.77	5.07	**10.34**[b]	15.20*[c]
12	3.2833	3.76	6.77	10.53	7.87	**12.68**	18.65*
13	3.0395	6.12	11.02	17.15	12.33	**15.68**	23.05*
14	2.9577	8.49	15.29	23.78	16.66	**18.43**	27.11*
15	2.9614	11.19	20.15	31.34	**21.40**	21.15	31.11*
16	2.6695	15.44	27.79	43.23	**28.44**	24.84	36.52*
17	2.5105	19.84	**35.71**	55.55	35.48	28.36	41.71*
18	2.2531	25.68	46.23	**71.91***	44.64	32.33	47.54
19	2.3248	30.44	54.79	**85.23***	51.65	35.63	52.39
20	2.3354	35.97	64.74	**100.71***	59.57	39.27	57.75
21	1.9678	44.10	79.38	**123.48***	71.39	44.09	64.84
22	2.2464	49.26	88.66	**137.91***	77.96	47.42	69.73
23	2.5037	55.01	99.01	**154.02***	85.12	50.99	74.98

Swtmbr = sawtimber; Med. Gr. = medium grade; Fbrstrd. = fiberstrand

[a] Shading represents the assumed "unlikely" range of sawtimber prices for diameter classes considering the average tree grade.

[b] Values in bold indicate the highest value in a diameter class when comparing the "likely" range for sawtimber, medium grade plywood peeler, and fiberstrand at $17/ton.

[c] An * indicates the highest value in a diameter class when comparing the "likely" range for sawtimber, medium grade plywood peeler, and fiberstrand at $25/ton.

DISCUSSION

This analysis shows the importance of competitive pricing for yellow poplar markets. When fiberstrand prices are low ($17/ton), all three markets establish a diameter range in which they can out-compete the others. However, with the increase in the unit price for one market (in this case the fiberstrand market unit price increases to $25/ton), the dominance range of each product market is affected. As demonstrated by the second comparison, the dominance range of the plywood peeler market was completely eliminated.

It is also interesting to note the competitiveness of the plywood peeler and fiberstrand markets with the sawtimber market at different grade prices. At grade 3 sawtimber prices, the plywood peeler market completely dominates the sawtimber market. Even at $17/ton prices for fiberstrand, the sawtimber price values only remain higher at diameters of 21 in. or greater. It therefore seems practical that grade 3 yellow poplar trees would receive higher dollar values used for either the fiberstrand or plywood peeler market. This trend provides evidence for the hypothesis that the plywood peeler market's primary advantage is that plywood peeler logs consistently receive medium grade and therefore can always outcompete the low grade sawtimber market.

At the other extreme, grade 1 sawtimber prices, the plywood peeler market is entirely out-competed. The fiberstrand market's dominance range extends only into the lowest diameter classes. At $17/ton and $25/ton, the dominance range for the fiberstrand market extends only to the 12- and 14-in. diameter classes, respectively. These ranges provide evidence that high quality grade 1 trees and/or logs always achieve higher prices in the sawtimber market except at the very lowest range of diameters.

To demonstrate the economic implications of merchandising, an example of a harvest scenario is provided. The diameter distribution for an acre of yellow poplar (table 5) was taken from McGee and Della-Bianca (1967). The stand selected has a site index of 100, is 50 years old, and has 131 square feet of basal area. The value per acre presented in table 6 assumes the acre is to be harvested entirely for each of the three product classes or be merchandised. Merchandising in this example allots all of the trees in each diameter class to the highest value market for that diameter class (those values in bold in table 4). In this example, the figure of $17/ton is used for fiberstrand price and the "likely" range is used for sawtimber price. An increase of 29 percent for the value of an acre is attained by merchandising over the next best option in this example, sawtimber.

Table 5.—*Diameter distribution for an acre of yellow poplar with site index 100, age 50, and basal area of 131 square feet per acre (McGee and Della-Bianca 1967)*

Diameter Class	11	12	13	14	15	16	17	18	19	20
Number of trees	14	13	13	12	11	10	9	7	5	1

Table 6.—*Dollar values for an acre of yellow poplar harvested entirely for each of three product markets and the value of the same acre harvested using merchandising. Values are delivered to mill prices.*

	Sawtimber only	Plywood peeler only	Fiberstrand only	Merchandising
Value/Acre	$2016.81	$2002.92	$1914.62	$2606.02

These dollar values are delivered to mill prices and do not reflect transportation or sorting costs. Also, the volumes listed by diameter class are individual tree volumes, which is not separated into graded logs. It is unlikely that an entire tree would receive grade 1 sawtimber prices for all the logs within that tree. Therefore, the range of prices listed for the three grades of sawtimber for each diameter class must be viewed to show the range of values for a tree of a given diameter. However, this analysis does provide evidence of market trends for yellow poplar in eastern Kentucky. This evidence supports the following general trends: (1) plywood peeler markets out-compete low-grade sawtimber markets, (2) high-quality logs achieve higher value in the sawtimber market except in the lowest diameter classes, (3) the fiberstrand market out-competes all markets (even grade 1 sawtimber) in the lowest diameter classes, and (4) an increase in the unit price by one market disrupts the diameter range at which all markets out-compete one another.

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SITE-SPECIFIC GROWTH AND YIELD SIMULATION FOR FAST GROWING EVEN-AGED STANDS

Lee R. Cunningham[1]

ABSTRACT.—South Africa is blessed with a warm, temperate climate and this results in the fast growth of our timber species. Rotations range from 6 to 30 years, depending on the species and the final product. With these short rotation periods and the limited availability of land suitable for forestry, it is essential for forest managers to accurately predict the growth of the crop. The growth and yield simulator (GYS) is a software tool that addresses this need. Built on an ArcView® platform, the GYS accesses site variables from the spatial data base and with the input of silvicultural regimes from the user, it is able to predict all the growth variables necessary for decision making. The GYS runs on growth prediction coefficient sets, which are set up by the user to predict the growth of a particular species based on the rotation length and the site. The output of the GYS is shown on basic graphs, and various scenarios can be viewed on top of each other. The total output data set can be saved to a database, which in turn can be viewed and interpreted through ArcView®.

INTRODUCTION

South Africa is self-sufficient in wood and paper, but is destined to deplete its supplies by 2020 if its current rate of population growth does not decrease. South Africans already manage their plantations intensively, with rotations varying from 30 years for sawtimber down to as little as 6 years for pulpwood. Present management regimes are based on espacement experiments established as far back as 1930, and often these regimes are applied as a standard without any consideration to the site qualities. The development of GIS technology has enabled South Africans to incorporate soil, climate, and biotic factors to design and implement a site classification system specific to their timber species.

Only 2 percent of South Africa is suitable for afforestation, and this land is in short supply primarily because agriculture occurs in the same area. The key objective of the local forestry companies is to maximize the production from their current land holdings. This goal can only be achieved through a forest management system that incorporates site classification and district-specific growth and yield models.

THE SITE CLASSIFICATION SYSTEM

Site classification within the context of South African forestry is usually performed at a scale of 1:10,000. The term site is defined as a homogenous area that has a unique composition of climate, topography, geology, and soil type. Sites are often described as "areas of homogenous silvicultural practice."

The most common characteristic from the site classification to be used in growth and yield prediction is site index. Site index is defined as the predicted height of a particular species for a given age, usually 20 years for sawtimber (SI_{20}). Actual tree growth data and site characteristics help determine site index equations for each of the major timber species. From these equations, site indices for each site are predicted. Figure 1 maps different site types across various compartments.

THE GROWTH AND YIELD SIMULATION

By viewing the plantation coverage, the forest manager can now select the compartment on which he wishes to perform the simulation. Once selected, the growth and yield simulator (GYS) can be accessed via a custom ArcView® interface. Figure 2 shows the beginning screen of the GYS.

Various sections within the GYS require user input before the simulation can take place (fig. 3). The user first needs to define which growth and yield model configuration is best representative of the area. Each coefficient set represents a particular species for a specific district. The choice of prediction method is associated with the coefficient set.

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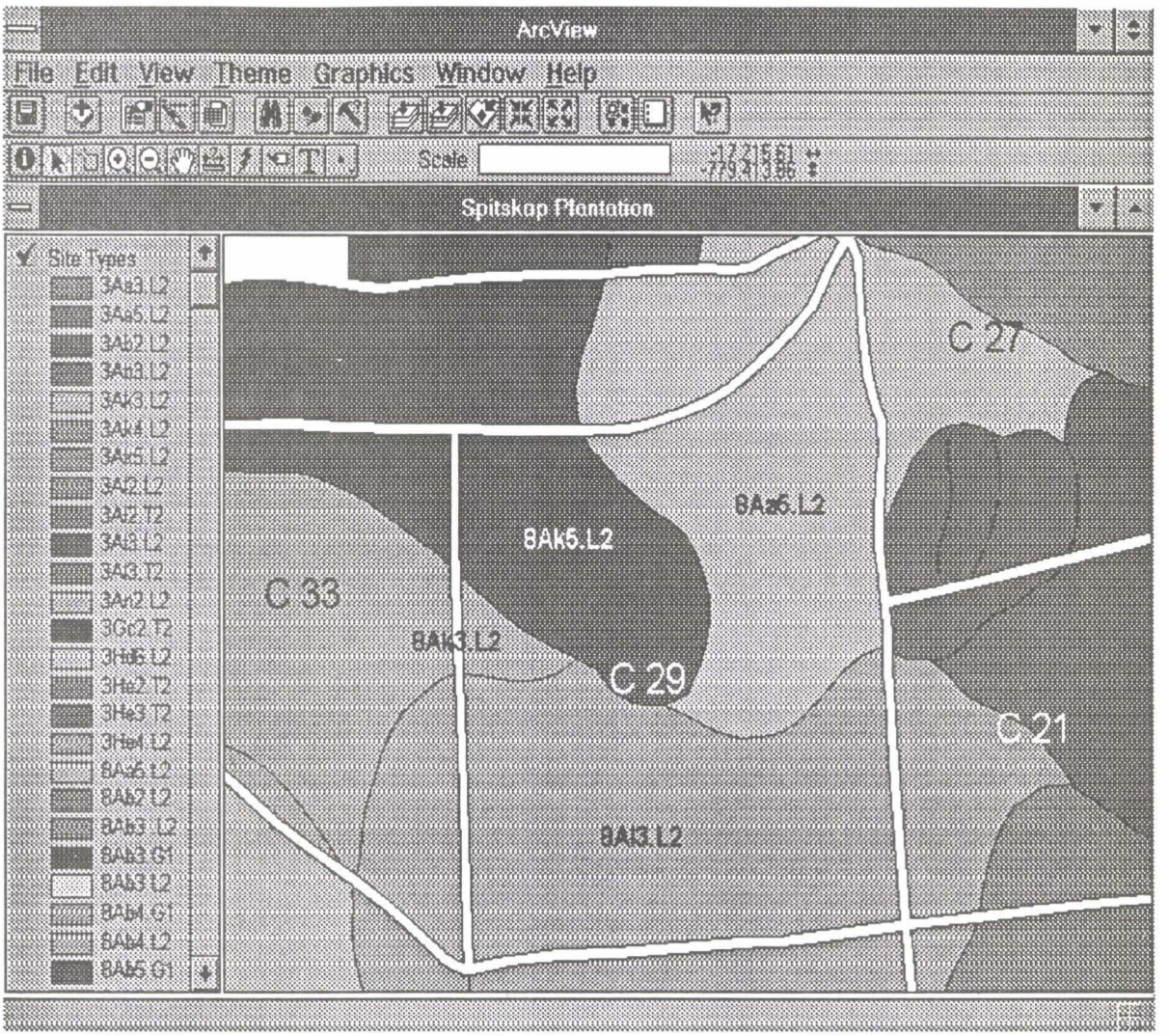

Figure 1.—*Map of compartments and site types.*

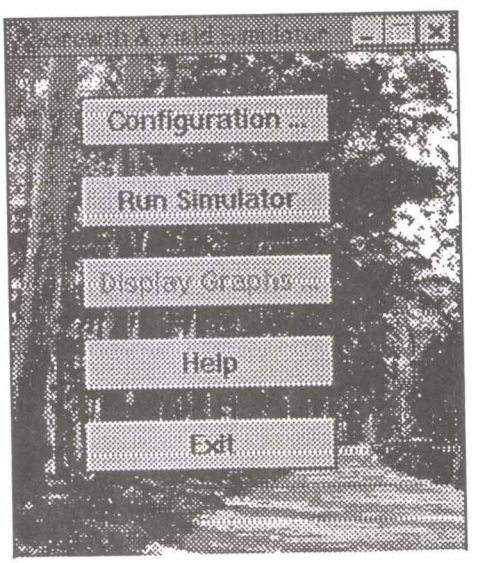

Figure 2.—*The beginning screen of the GYS.*

If the stand is to be grown on a sawtimber rotation, then thinning and pruning regimes need to be included. The thinning regime can be a function of either age, quadratic diameter, or relative spacing (fig. 4).

The pruning regime can be a function of either age or a limiting diameter (fig. 5). Further options include whether the user requires diameter at breast height (d.b.h.) distributions at thinnings and at clear-felling. If a financial analysis is to be carried out, then the d.b.h. distribution prediction is a necessity. Height growth prediction can be done two different ways. If there is enumeration data, the height measurement can be used for a projection of a future height, otherwise the site index can be used for prediction. Young stands or unplanted areas generally do not have enumeration data. If one selects the site index method, then the simulator reads in a weighted mean site index for the chosen species. Once the configuration is set, the program can be run.

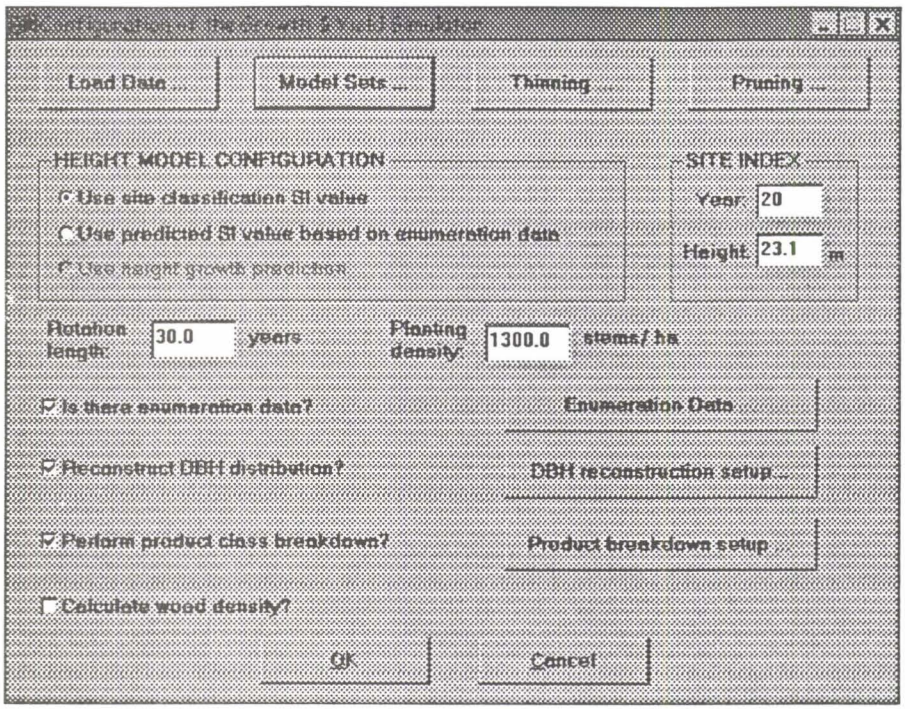

Figure 3.—*Configuration screen of the GYS, where the user inputs information about the site type.*

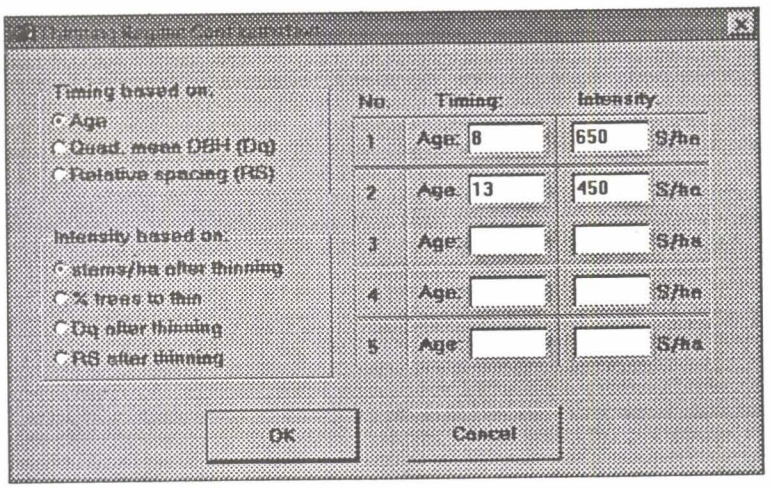

Figure 4.—*The thinning regime configuration screen of the growth and yield simulator.*

Output from the program is presented in two ways. The first is a series of small graphs that indicate the growth trends of different variables, i.e., d.b.h., height, volume, and basal area. The second method of presentation is output data saved as a dBase file that can be used later from ArcView®. The output scenario can be saved and after changes have been made to the original configuration, the new output can be viewed with the original scenario.

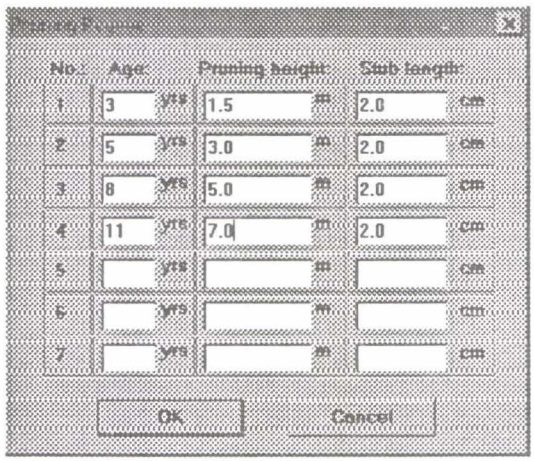

Figure 5.—*The pruning regime configuration screen. The screen shows a regime that is a function of age.*

AN EXAMPLE

Compartment C29 (fig. 1) is to be planted for a softwood sawtimber market. It consists of four different site types, each of which have a site index for three species—*Pinus patula, P. taeda,* and *P. elliottii* (table 1).

The first run is done with *P. patula* as the species of choice. The coefficients are set for *P. patula* in the same area. The weighted average site index is 23.1. The age-based thinning regime is as follows:

- Established at 1,300 stems per hectare (spha),
- Thinning at 8 years to 650 spha,
- Thinning at 13 years to 450 spha, and
- Harvested at 30 years.

The pruning regime consists of four lifts and is also age related:

- 3 years: 1.5 meters,
- 5 years: 3.0 meters,
- 8 years: 5.0 meters, and
- 11 years: 7.0 meters.

Figure 6 shows the output of the run for the three species. The change in volume for every thinning can be seen.

Runs for all the species are done, keeping the thinning and pruning regimes constant. The results from the growth and yield simulations are used to determine the Land Expectation Value (LEV) and the Net Present Value (NPV) for each of the species (table 2).

Table 1.—*Compartment C29's four different site types with their areas, site indices for the three Pinus species, and the weighted average for the whole compartment*

Site type	Area	Site indices		
		P. patula	*P. elliottii*	*P. taeda*
	ha	- - - - - - - - *meters at 20 years* - - - - - - - -		
8Aa5.L2	4.236	24.5	24.0	24.3
8Ak5.L2	2.740	24.7	24.2	24.4
8Al3.L2	6.122	21.5	22.2	20.9
8Ak3.L2	0.355	21.8	23.2	21.1
Total	13.453			
Average		23.1	23.2	22.7

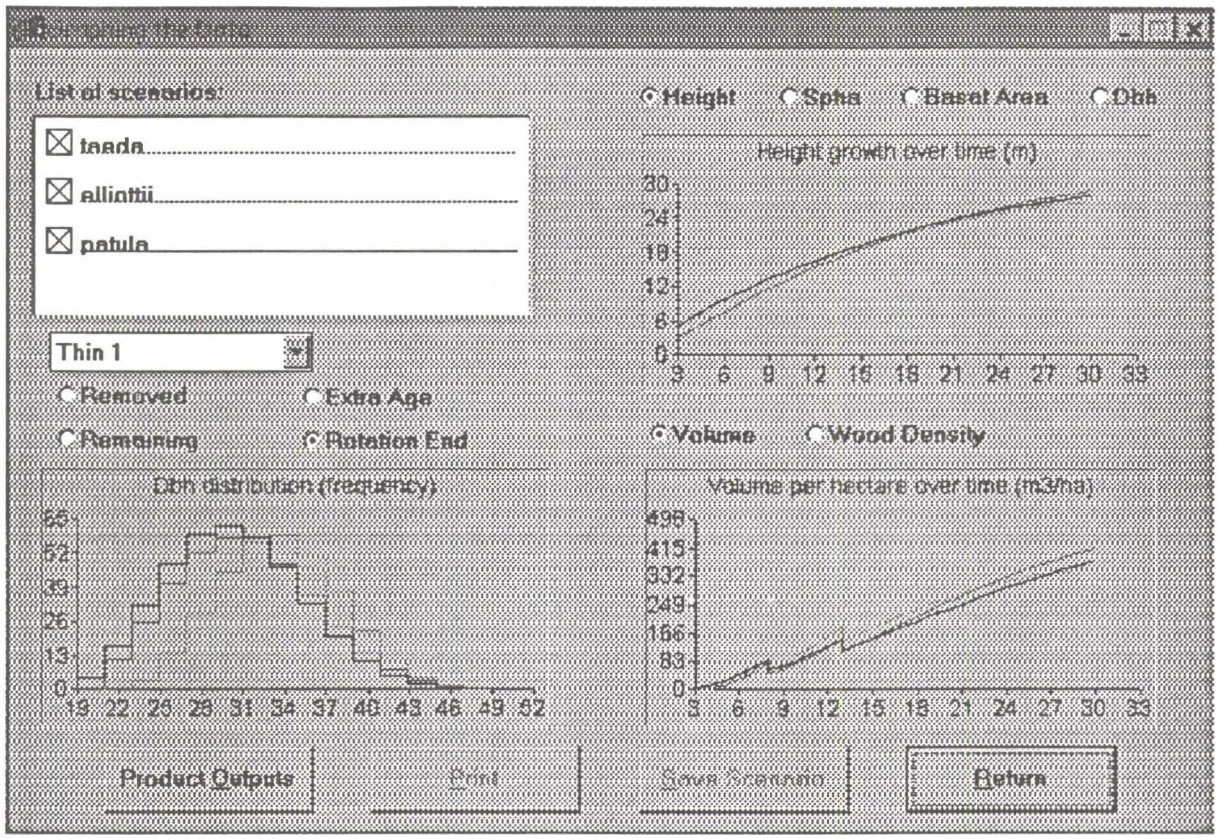

Figure 6.—*Output of the GYS run for the three species in Compartment C29.*

Table 2.—*The results of the growth and yield simulations in terms of utilizable volumes, Land Expectation Value (LEV), and Net Present Value (NPV) for the three different* Pinus *species*

Species	Utilizable volume	Terminal value	LEV	NPV
	m^3/ha	- - - - - - - - - - - - - - - -	R/ha	- - - - - - - - - - - - - - - -
Pinus patula	311.85	79,178.18	4,088.02	8,393.09
Pinus elliottii	412.05	107,951.79	14,166.37	15,756.35
Pinus taeda	203.68	53,225.85	-4,654.73	1,979.20

R = Rand, the monetary unit of South Africa. May 1997 exchange rate: US$1.00 = R4.50.

The first thing we notice in table 2 is that the LEV for *Pinus taeda* is negative. This is relatively common within South African forestry because the value addition takes place during the timber processing procedure. Most of the forestry companies have vertical structuring (i.e., both the plantations and the processors are owned by the same company). Another reason for the negative values is the high nominal cost of capital at 3.36 percent due to the high inflation rate and the poor financial control exhibited within the country. Although the site indices for *P. patula* and *P. elliottii* are very similar, the differences in financial criteria are much larger. The reason for this is the quality-based log grading system that benefits growers that adhere to a sound pruning practice that promotes the formation of knot-free timber.

MODELING THE DIAMETER DISTRIBUTION ON THE FULLY STOCKED HARDWOOD PERMANENT SAMPLE PLOTS

Eldon Gunn, Ed Bailey, and Tim McGrath[1]

ABSTRACT.—The purpose of this work was to develop a diameter distribution model that adequately represents the observed data from Nova Scotia's fully stocked research Permanent Sample Plots (PSP). We have been able to develop a family of Weibull distributions whose parameters depend only on the stand average diameter. Using both chi-square and Kolmogorov Smirnov tests, we tested the hypothesis that the distribution of diameters observed on individual plots is from that member of this family of distributions whose parameters correspond to the plot mean diameter. At the 99 percent level we would not reject this hypothesis on all except 10 of the 283 plot samples. At the more stringent 95 percent level, we reject this hypothesis only for 32 out of the 283 plots.

INTRODUCTION

This work came about while completing the normal yield tables for Nova Scotia hardwoods since we wanted to have a quantitative description of the diameter distribution of the trees making up a stand. In the older softwood normal yield tables (Nova Scotia Department of Land and Forests 1990), this distribution of diameters is given as three numbers, namely the volume available in diameters larger than 1.5, 9.1, and 14.1 cm diameter at breast height (d.b.h.). These indicate total volume plus merchantability limits of two classes of products. The problem with this approach is that critical diameters for merchantability change depending on harvest technology being used. Another reason for investigating the development of a diameter distribution is to enhance the capabilities of the Nova Scotia Geographic Information System (GIS). The GIS data will include only a single stand average diameter. The ability to project a diameter distribution from this single number will be useful in developing quantitative assessments of the forest cover and of its economic value.

There is a long history of using the Weibull distribution to model diameter distributions (Clutter *et al.* 1983, Bailey and Dell 1973). Obviously, this influenced us to use the Weibull as our distribution of choice. The Weibull distribution requires the estimation of three parameters. For any given stand, it is not difficult to estimate the parameters that best describe that stand. A standard technique involves Maximum Likelihood Estimators (MLE). Law and Kelton (1989) discuss parameter estimation in general and give methods for several standard distributions, including the Weibull. The derivation of MLE's for the Weibull was originally given by Harter and Moore (1965). Bailey and Dell discuss various approaches taken to estimation of these parameters for forest stands.

Our problem is unusual in that we do not want to estimate the parameters for any particular stand. Rather, we want to develop a continuous family of distributions that depend only on the single variable of stand average diameter. This paper thus attempts to answer two questions. First, how can we develop the parameters of the Weibull distribution as a function of stand average diameter? Second, does the family of distributions do a reasonable job of describing the distribution of diameters when applied to any particular stand? As will become evident, our approach is heuristic in two aspects. First, most natural stands have an understory with trees of very small diameter. These are often large in number but insignificant in basal area. If these are included in the diameter distribution, this will almost inevitably mean a bimodal distribution. We developed a screening mechanism designed to filter these from our data base. Second, fitting the location parameter for a Weibull is somewhat problematic. Our choice here has been heuristic and is open to criticism. However, it appears to work well and we will argue that it does not significantly influence the results.

Briefly, our approach has been to first group the data from our plots into diameter class "superplots". We then

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carry out MLE estimates of the parameters for each superplot and attempt to fit smooth curves to these parameter estimates using the average diameter of the superplot as the variable to be regressed against the parameter estimates. It turns out that the curves we fit are quite reasonable approximations to the MLE estimates. The correspondence between the superplot histograms and the density functions is very strong. Even more encouraging, if we apply the Weibull functions to the individual plots, a very large portion of the plots give good hypothesis testing results.

We originally expected that the diameter distributions of treated (thinned) stands would be greatly different from the natural stands that we used for the normal yield tables. We were surprised to find that this was not the case. The results of hypothesis testing using the Weibull distributions on the entire set of research permanent sample plots (PSP's) gave results very comparable to tests restricted to the fully stocked control plots that we use for the normal yield tables.

OUR PROCEDURE

The data was taken from Nova Scotia's PSP's. There are 80 plots identified originally as the fully-stocked stands used to represent the normal yield. Most were first measured in 1978 and remeasured every 5 years since. We have a total of 283 plot measurements. As is common practice, we treat the remeasurement data as independent samples.

Our approach is to first group the data from the individual PSP's according to plot average diameter ($\bar{d}$). We used 1 cm diameter classes. It is important to clarify what we mean by the average diameter d of the trees on the plot.

The $\bar{d}$ is the diameter of the tree of average basal area on the plot. Thus if we have sample diameters from n trees on the plot ($d_1, d_2, \ldots, d_n$), then:

$$(1) \qquad \bar{d} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

The Weibull distribution has a simple analytic form. There are three parameters, commonly referred to as the location (λ), scale (β), and shape (α) parameters. Using these parameters, if the random variable D, the diameter of a tree on a plot, has a Weibull density function f(D), then

$$f(D) = \alpha\beta^{-\alpha}\,(D-\lambda)^{\alpha-1}\, e^{-((D-\lambda)/\beta)^{\alpha}} \text{ if } D > \lambda$$
$$= 0 \qquad \text{otherwise}$$

and the corresponding cumulative distribution function is F(D) where

$$F(D) = 1 - e^{-((D-\lambda)/\beta)^{\alpha}} \qquad \text{if } D > \lambda$$
$$= 0 \qquad \text{otherwise.}$$

As indicated earlier, we set out to find an expression for α, β, and λ as a function of stand average diameter and to then test the performance of this family of distributions.

The Insignificant Basal Area Test

Almost every plot contains a number of small trees that are unlikely to become crop trees because they are undergrowing the main stand. This may correspond either to ingrowth or to older trees that have always been suppressed in the stand. A quite typical situation is small-diameter American beech undergrowing larger-diameter sugar maple. These trees may be quite numerous but make up an insignificant fraction of the basal area of the main stand. If we take the time to examine the trees on the plot manually, it is usually not too hard to decide which trees have no potential as crop trees. However, we need an automated procedure for routine processing. We developed a screening test that has proven to be quite effective. Our approach is based on the idea of a basal-area-weighted average diameter ($\hat{d}$). The calculation is:

$$\hat{d} = \sum_{i=1,n} d_i \frac{d_i^2}{\sum_{j=1,n} d_j^2} = \frac{\sum_{i=1,n} d_i^3}{\sum_{j=1,n} d_j^2}$$

The idea is to delete trees that have an insignificanteffect on this basal-area-weighted diameter. The test quantity we use is $d_{test} = 0.10\,\hat{d}/n$ and we discard a tree if $\dfrac{d_i^3}{\sum_{j=1,n} d_j^2} < d_{test}$.

The motivation of this test is that, since $n\,d_{test} = 0.1\,\hat{d}$, it is impossible to discard enough trees to change this basal-area-weighted diameter by more than 10 percent.

Using the example plot 3911, $\sum_{j=1,n} d_j^3 = 9925.2$, and there are 28 trees with positive diameter for an average diameter $\bar{d} = 18.5$ (fig. 1). The $d_{test} = 0.0736$ so that we discard any trees with $d_i^3 < 0.0736 * 9925.2 = 730.49$, which corresponds to $d_i < 9.006$ cm. Applying this test to the plot 3911, we get the figure 2 histogram where the left-hand column now contains both the dead and discarded trees. The average diameter of the remaining trees is $\bar{d} = 21.12$ cm.

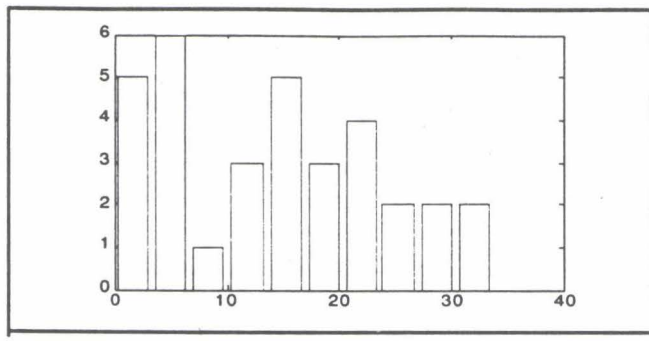

Figure 1.—*Histogram of diameters on plot 3911, 1988.*

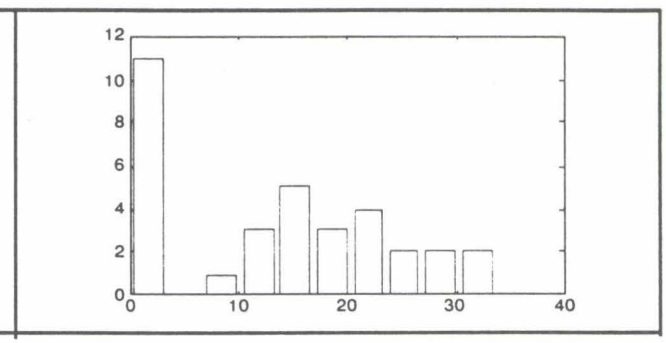

Figure 2.—*Histogram of diameters on plot 3911, 1988 after applying test for insignificant basal area.*

Plot 3911 in 1988 illustrates the problem. As indicated in figure 1, there are 5 dead trees on the plot. The larger trees are all sugar maple. There are three beech with diameters less than 4 cm and three white spruce with diameters from 4-6 cm. The next smallest tree has a diameter of 9.3 cm.

We applied this discarding procedure for trees of insignificant basal area to all of the plots. Trees were discarded for 106 of the 283 plots. Only 13 plots were problems in the sense that the deleted trees accounted for more than 5 percent of basal area. In no case did the discarded trees account for more than 7 percent of the total basal area of the plot even though, in some cases, more than half of the total trees were discarded (e.g., plot 4111 in 1978). This procedure is simple and quite effective.

Grouping into Diameter Classes

After deleting the trees of insignificant basal area from each plot, the average diameter $\bar{d}$ was calculated for the plot, and all the remaining trees on the plot were added into the diameter class corresponding to the plot average diameter $\bar{d}$. As indicated earlier, we used 1 cm diameter classes for the aggregation. We computed the average and the minimum diameter in each diameter class. The results are shown in table 1. We plotted the minimum diameter as a function of the average diameter of the d.b.h. class, the results are shown in figure 3. Although a straight line represents the minimum diameter very well, we fit a regression line to a second-order equation. The least squares fit leads to the following function.

$$\text{Minimum diameter} = 0.4240\ \bar{d} - 0.0020\ \bar{d}^2$$

This function is plotted on figure 3. The line below it is half of the minimum diameter line. A natural question arises as to how to deal with this minimum diameter. On the one hand, we could ignore it completely and try to fit Weibull distributions in which the location parameter $\lambda = 0$. However, since there is such a strong trend in the minimum diameter, we have decided to make use of this in developing a location parameter for the diameter distributions. Our approach has been simple in the extreme. We cannot use the curve of minimum diameter directly since this is only a least squares fit to sample data and some observations lie below this curve. The Weibull distribution implies that it is not possible to have any observations that lie below the location parameter. Our simple choice has been to use 75 percent of the minimum diameter line for our location parameter. As will be seen, this simple choice gives good results. However, it may be worthy of further investigation.

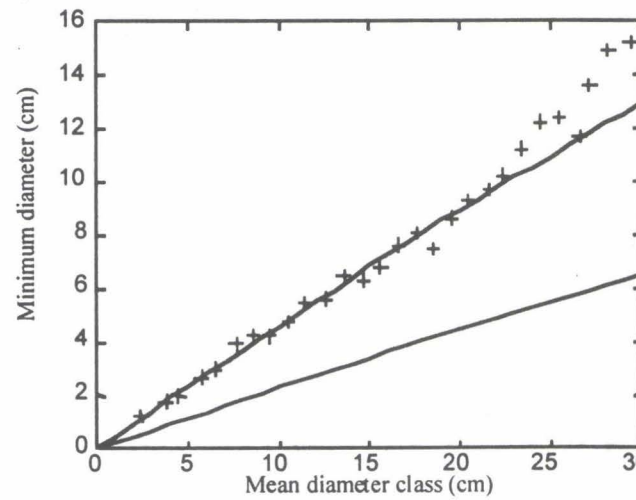

Figure 3.—*Plot of minimum diameter as a function of class average diameter.*

Table 1.—*Statistics on diameter classes*

d.b.h. Class	Number of trees	Class average diameter	Class minimum diameter
cm		*cm*	
2–3	103	2.377	1.200
3–4	51	3.710	1.800
4–5	74	4.476	2.000
5–6	279	5.670	2.700
6–7	293	6.450	3.000
7–8	354	7.561	3.900
8–9	227	8.515	4.200
9–10	259	9.460	4.200
10–11	271	10.474	4.800
11–12	251	11.402	5.500
12–13	282	12.547	5.600
13–14	363	13.549	6.500
14–15	675	14.648	6.300
15–16	619	15.588	6.800
16–17	717	16.583	7.600
17–18	742	17.600	8.100
18–19	858	18.543	7.500
19–20	607	19.530	8.600
20–21	488	20.409	9.300
21–22	312	21.554	9.700
22–23	129	22.389	10.200
23–24	102	23.370	11.200
24–25	72	24.472	12.200
25–26	99	25.49	12.400
26–27	52	26.580	11.700
27–28	45	27.116	13.600
28–29	21	28.185	14.900
29–30	20	29.434	15.200

MLE Estimates of Shape and Scale Parameters

Once the location parameter is given, MLE estimates of the shape and scale parameters can be computed from equations originally developed by Harter and Moore. Law and Kelton give a simple Newton step iteration. This calculation was programmed in a FORTRAN program called Calcparms.f that is available from the authors. Convergence to four significant figures of accuracy is obtained in only three or four iterations.

Table 2 gives the results of the MLE estimates of α and β for each d.b.h. class. If we plot the β's as a function of class average diameter, we see that a straight line fits them extremely well (fig. 4):

$$\beta = -0.2959 + 7757\,\bar{d}.$$

The behavior of the α's is not as smooth as seen in figure 5. A least squares fit to a quadratic model gives:

$$\alpha = 2.6744 - 0.0101\,\bar{d} + 0.0003\,\bar{d}^2.$$

If we use the MLE estimates for α and β directly, it turns out that even though β varies smoothly as a function of d, the density functions do share this property. Figure 6 illustrates the problem where the transition between diameter distributions is not as smooth as it might be. This is due to the jumpiness of the MLE estimates of α.

To complete our estimation process, we used the equation derived for α and reestimated the β. Once again, a straight line fits the β's extremely well, but with slightly different parameters:

$$\beta = -0.2877 + 0.7784\,\bar{d}$$

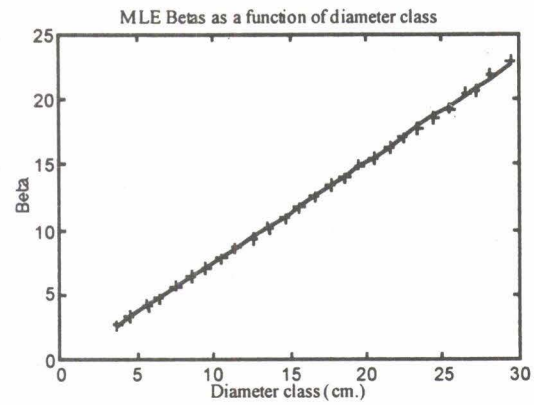

Figure 4.—*MLE Beta s as a function of diameter class.*

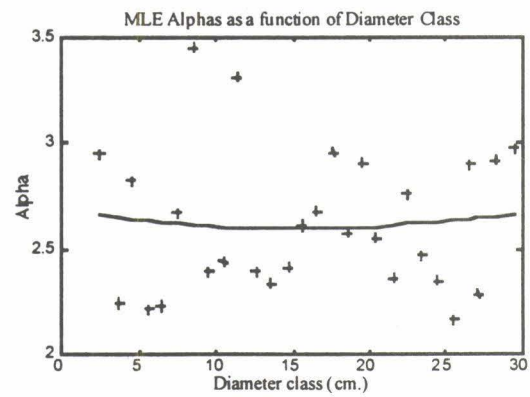

Figure 5.—*MLA Alpha s as a function of diameter class.*

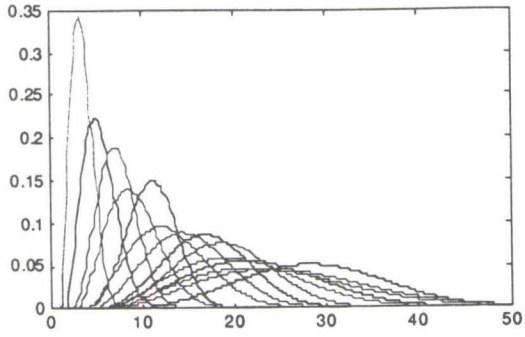

Figure 6.—*Diameter distributions resulting from the MLE estimates of α and β.*

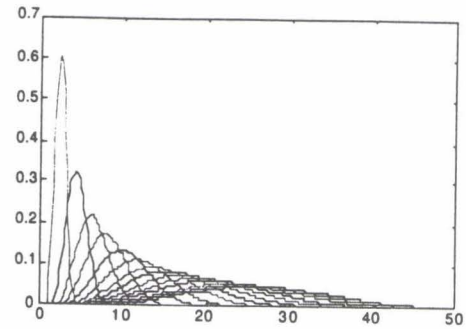

Figure 7.—*Diameter distributions resulting from smoothing the MLE estimates of α and β.*

Table 2.—*MLE estimates of the shape and scale parameters*

d.b.h. Class	Number of observations	Average diameter	Location Parameter (λ)	Shape Parameter(α)	Scale Parameter (β)
cm		*cm*			
2	103	2.387	0.751	2.95248	1.75791
3	51	3.710	1.159	2.24311	2.69253
4	74	4.488	1.397	2.81771	3.31149
5	279	5.675	1.756	2.21469	4.12462
6	293	6.455	1.990	2.23072	4.70491
7	354	7.565	2.320	2.67054	5.60782
8	227	8.516	2.599	3.44816	6.36526
9	259	9.463	2.875	2.39152	6.98182
10	271	10.479	3.168	2.43799	7.76027
11	251	11.404	3.431	3.31249	8.57024
12	282	12.549	3.754	2.39408	9.31638
13	363	13.551	4.034	2.33548	10.05730
14	675	14.651	4.337	2.40972	10.92155
15	619	15.589	4.593	2.61117	11.71793
16	717	16.585	4.861	2.67427	12.50934
17	742	17.601	5.132	2.95346	13.36265
18	858	18.546	5.382	2.57950	14.00911
19	607	19.531	5.639	2.90072	14.87957
20	488	20.411	5.866	2.55067	15.47276
21	312	21.556	6.158	2.35983	16.28445
22	129	22.390	6.368	2.75982	17.11851
23	102	23.371	6.613	2.46647	17.78338
24	72	24.473	6.884	2.34868	18.60066
25	99	25.495	7.132	2.16640	19.22892
26	52	26.581	7.393	2.90041	20.50533
27	45	27.116	7.520	2.28428	20.64206
28	21	28.185	7.771	2.91684	21.85245
29	20	29.434	8.061	2.97601	22.88152

As seen in figure 7, there is now a much smoother transition between diameter class distributions.

VERIFYING THE MODELS

The approach outlined results in a model of diameter distributions that can be summarized as:

Location Parameter

$$\lambda(d) = 0.4240\,\bar{d} - 0.0020\,\bar{d}^2$$

Shape Parameter

$$\alpha(d) = 2.6744 - 0.0101\,\bar{d} + 0.0003\,\bar{d}^2$$

Scale Parameter

$$\beta(d) = -0.2877 + 0.7784\,\bar{d}$$

Using these parameters, the random variable D(d), the diameter of a tree on a plot with average diameter d, has a Weibull density function (all the parameters and variables are to be thought of as functions of d):

$$f(D) = \alpha\beta^{-\alpha}(D-\lambda)^{\alpha-1} e^{-((D-\lambda)/\beta)\alpha} \text{ if } D > \lambda$$
$$0 \qquad \text{otherwise}$$

We have two approaches to verifying that our procedures have led to valid results. In figure 8, we show the density functions versus a histogram of the data for several diameter classes. As is visually evident there, the fits are very good. Note that there are quite a few trees in these histograms. For example, as seen in table 2, the 14 cm class has 675 trees.

This does not, however, answer the question as to how well the distributions represent any given plot. The approach that we have taken here is based on hypothesis testing

Testing Hypothesis of Weibull Distributions

We ran all of the individual plots through both Kolmogorov Smirnov (KS) and Chi Square hypothesis tests (a FORTRAN program for doing this is available from the authors). At the 95 percent level with the alpha and beta parameters computed from the mean diameter, we would reject the hypothesis that the distribution observed comes from the Weibull distribution, for only 32 of the 286 combinations of plot and year of remeasurement using any one of the tests. More details are shown in table 3 below. Not all plots rejected by the KS test were rejected by the Chi Square test and vice versa. Only 10 plots can be rejected at the 99 percent level. Since the distributions were developed from the aggregated diameter classes, this would appear to be a quite reasonable confirmation of the validity of the approach.

Even if all of the plots really were from our Weibull distributions, we would have expected to see 14 (283x5 percent) and 3 (283x1 percent) rejects at the 95 percent and 99 percent levels, respectively. Thus, these are quite encouraging results. The problem plots are confined to 20 of the 80 physical plots. Of the total 32 rejected plot-measurement combinations, 18 of these can be accounted for by 6 plots (561, 2911, 961, 2271, 3811, and 3671). Moreover, as we discuss below, in looking at some of these plots, we can question whether they should be considered typical of plots that we should use to construct normal yield tables (even-aged, fully-stocked stands).

Some Problem Plots and Good Plots

We plotted the histograms for some of the problem plots. These include the problem plots 961, 3671, and 1711. In doing so, we have preprocessed the raw data using the test of insignificant basal area discussed above. Any such plots are given a diameter of 0, and thus appear in the histogram on the extreme left-hand column. This column may also include dead trees since these are assigned a diameter of 0 in the plot measurements (fig. 9).

Plot 961 had one tree of 58 cm in diameter in 1983. This tree can probably account for the rejection of the hypothesis. Plot 3671 is an example of a two-story stand measured in 1983. Plot 1711 in 1978 had a pronounced two-story structure. Although this still remains evident in 1983 and 1988, it is not strong enough in these later years to reject the Weibull hypothesis.

Table 3.—*Number of rejected plots using the Kolmogorov Smirnov and Chi Square tests at various levels on the 283 control plots*

	283 control plots hypothesis test level (%)			1122 permanent sample plots hypothesis test level (%)		
	95	97.5	99	95	97.5	99
Number of KS Rejects	13	6	3	63	42	29
Number of chi-square Rejects	27	16	10	112	71	47

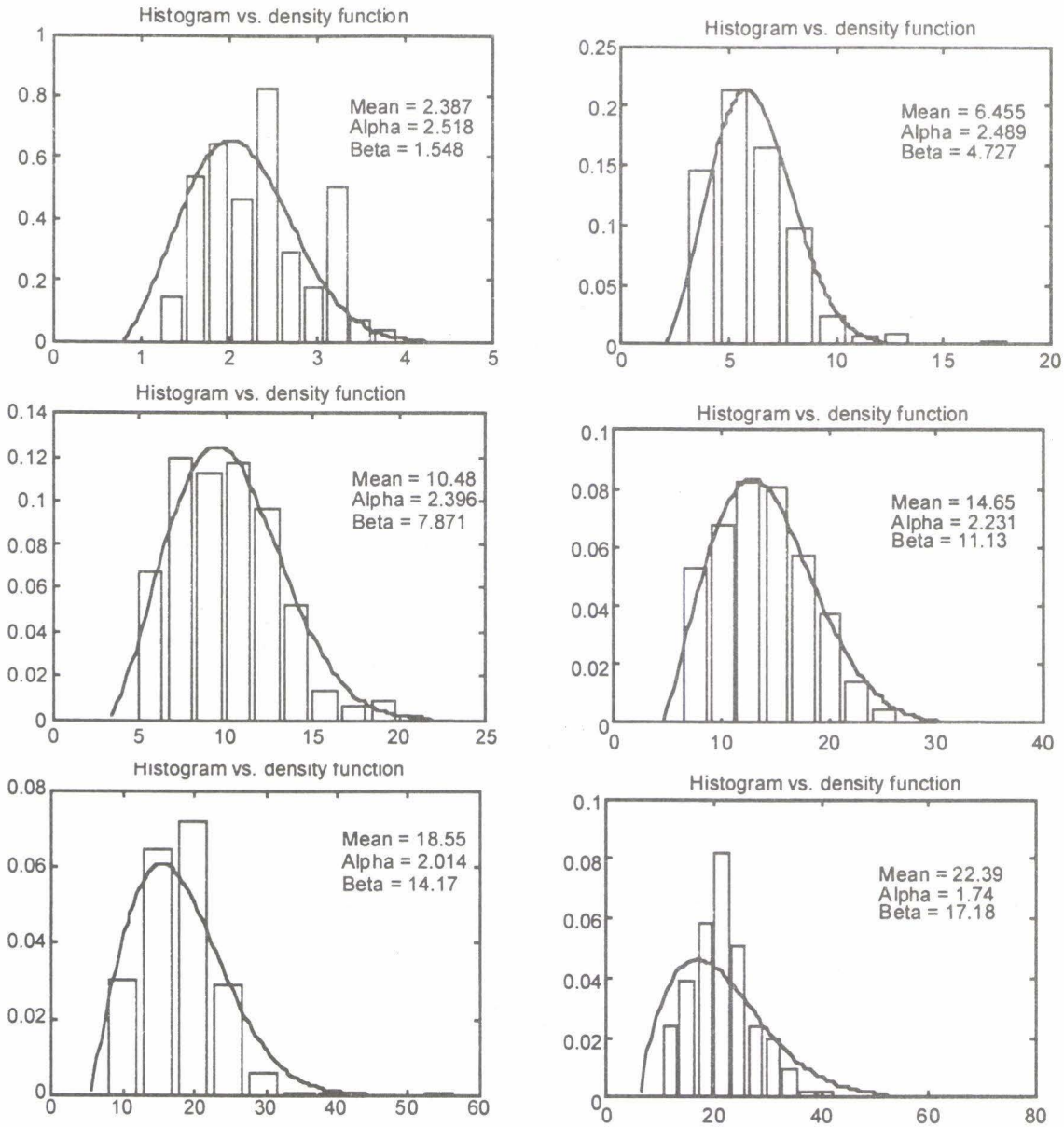

Figure 8.—*Plot of histogram vs. distribution for the 2, 6, 10, 14, 18, and 22 cm diameter classes.*

We selected plot 411 in 1978 to give some feel for the quality of fit for those plots not rejected by our hypothesis tests. Although a perfect fit cannot be expected, the degree of correspondence appears quite encouraging.

OTHER SITUATIONS: MANAGED STANDS

We have applied the ideas in this paper to a number of different situations including managed hardwoods and managed and unmanaged softwoods. The essential ideas appear to work well in all these cases, although there are some differences in the functional form of some of the models. These are reported elsewhere. One interesting point that we found is that there is so little difference in the diameter distributions between managed and unmanaged hardwoods that it is not unreasonable to use the same diameter distribution for both. In table 3 we show the results of the hypothesis tests for both the 283 control plots used for the normal yield tables and the 1,122 hardwood permanent sample plots that the Province maintains to investigate the effect of thinning and cleaning. As can be seen there, the percentage of rejected plots is virtually unchanged. These results were surprising to us initially. However, using a simple simulation

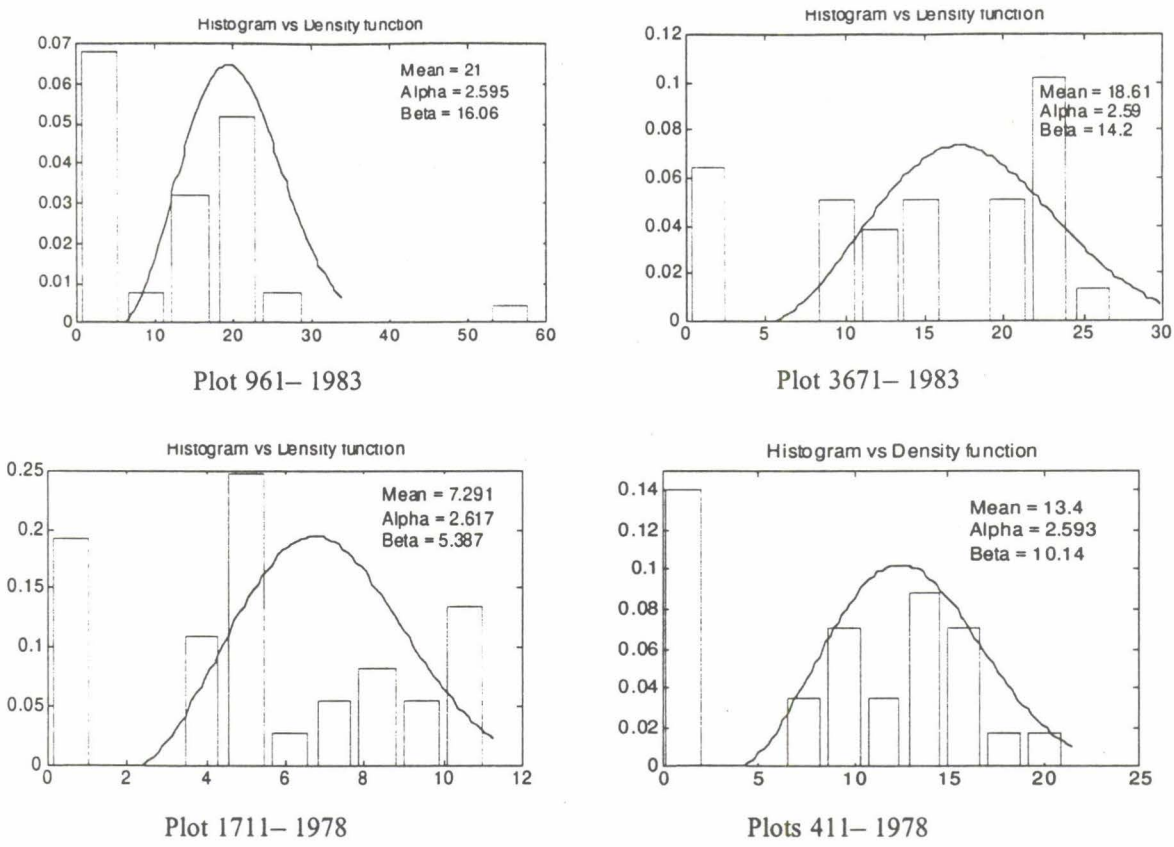

Figure 9.—*Histograms of some plot data and the fitted distribution.*

model, we have been able to offer at least a partial explanation (Gunn *et al.* 1997).

GENERAL CONCLUSIONS

In trying to model distributions, we do not have available a simple optimization principle equivalent to the least squares fit that underlies conventional regression modeling. Instead, the onus is on the modeler to choose a "reasonable distribution" with desirable properties, and then do hypothesis testing to establish whether it is defensible to persist in the belief that the distribution is reasonable in face of the data.

In the work reported here, we began with the belief that the Weibull is a reasonable class of distributions to use based on the long history of use of this family of distributions in modeling tree diameters. Our next step was one of aggregating the plot data into mean diameter classes and then calculating MLE estimates of the parameters of the Weibull distribution for each class. Proceeding on the belief that the parameters should vary smoothly from class to class, we fit low order curves through these parameter estimates to get continuous functions that give all three parameters (λ, α, β) as a function of stand average diameter. Note that other approaches are possible. For example, we could have calculated (MLE) estimates for the three parameters for every individual plot and then attempted to fit regression curves to this much larger (and probably more variable) set of points.

In comparing our density functions to the histograms of the class aggregate data, the correspondence is quite good. Even the visual test provides ample evidence of this. Some might argue that this good correspondence between the class aggregate data and the density functions that we have derived is all the verification that is necessary. In arguing this, one would take the view that class aggregates are more likely to give a clearer picture of province-wide average results than the results on any individual plot, and that the individual plots are not really relevant.

Although not necessarily disagreeing with the above viewpoint, we took the position that it would at least be interesting to learn the proportion of plots for which we would be forced to reject the hypothesis that the trees on that plot had diameters drawn from our calculated distribution (given the average diameter of the plot under consideration). We have tested this hypothesis for every plot using two different tests. In both cases, we conducted the tests under the assumption that we were given all parameters of the distribution. This assumption can be questioned in two regards. First, each plot did play a small part in estimating the parameters of the class within

which that plot fell. Second, the trees on the plot are used to compute the plot average diameter, which in turn leads to the calculation of α, β, and λ. Given that this assumption is valid, then we obtained the result that we reject the hypothesis that the plot data corresponds to our distribution only for quite a small proportion of cases, even at the 95 percent level. As a result we can conclude that our approach does provide a not unreasonable method for estimating diameter distributions for the type of stands represented by our data.

DISCLAIMER

The main purpose of this paper is to report on the process of developing the diameter distributions, not the results. The current recommended approach of the Nova Scotia Department of Natural Resources may have changed due to either updated data or a change of thinking within the Department. Anyone wishing information on Nova Scotia's hardwood normal yield tables should consult the Forestry Branch, N.S. Department of Natural Resources, P.O. Box 68, Truro, Nova Scotia B2N 5B8.

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EFFICIENT AND SUSTAINABLE FOREST STOCK AND HARVEST WHEN NONTIMBER BENEFITS ARE VALUED

Jianbang Gan; Stephen H. Kolison, Jr.; and Joe P. Colletti[1]

ABSTRACT.—This paper investigates the efficient steady-state forest stock and harvest when both timber and nontimber benefits are valued. The results indicate that forest stock should be thickened when nontimber benefit is valued in addition to timber benefit. In addition, the effect of the discount rate and the ratio of the marginal nontimber benefit to the marginal timber benefit on the optimal steady-state stock and harvest is of the same magnitude with opposite directions. The theoretical model is applied to the U.S. coniferous forests.

INTRODUCTION

Many studies have been undertaken to determine the optimal forest rotation length under different scenarios since the advent of the Faustmann formula. Some of these were focused on the optimal rotation length with the consideration of only timber value (Chang 1983, McConnell *et al.* 1983, Newman *et al.* 1985). Others searched for the optimal rotation length with the inclusion of both timber and nontimber benefits (Calish *et al.* 1978, Hartman 1976, van Kooten *et al.* 1995). These studies have provided important guidelines on when to cut trees in the even-aged plantations. However, their applications in uneven-aged, or natural forests, are limited because age is no longer an appropriate variable under such circumstances. Also, in formulating a forest management plan/policy, particularly in the management of a large-scale (such as a regional or national scale) forest resource, it may be more relevant to determine how much timber should be harvested and what level of the forest stock should be maintained than to know when trees should be cut. This will become increasingly important if nontimber benefits which largely depend on forest stock, are valued, and if sustainability needs to be addressed in forest resource management and utilization. Moreover, the optimal steady-state harvest level, unlike the optimal rotation age, can directly provide information on the long-run potential timber supply from a forest.

To this end, this article investigates the optimal forest stock and harvest with and without addition of nontimber benefits to the timber benefits. A theoretical optimal control model of forest management will be formulated. The model will then be solved to find the optimal steady-state forest stock and harvest levels. Finally, the western and eastern U.S. coniferous forests will be used as an empirical example to illustrate our theoretical results.

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THE MODEL

Forest production is a joint production process, in which inputs are transferred into multiple outputs (timber and nontimber products). The benefits derived from forests may consist of timber and nontimber benefits. Assume that the timber benefit is a function of the amount of the timber harvested (h), denoted by U(h), and that the nontimber benefit depends on the level of the forest stock (x), denoted by V(x). It is also assumed that only two inputs are involved in the forest production. One is a composite input, silvicultural effort (E) including all inputs except land needed to generate/regenerate and manage the forest for both timber and nontimber benefits. The other is forest land (L).

To develop a model which can be applied to different sizes of forest land without losing the generality, this analysis is based on a unit area of forest production, i.e., L=1. It may be rational to assume that forest production/management is to maximize the present value of net timber and nontimber benefits over an infinite time horizon subject to the constraints of the forest stock. Such a model for a unit area forest land can be formulated as follows:

$$\text{Max}_{h(t),E(t)} \int_0^{\infty} \{U[h(t)] + V[x(t)] - wE(t) - r\} e^{-\delta t} dt \quad (1)$$

subject to:

$$\frac{dx}{dt} = g[x(t), E(t)] - h(t) \quad (2)$$

(3) $x(0) = x_0$

(4) $x(t) \geq 0$

Here x(t) is the forest stock level at time t, h(t) is the timber harvest level at time t, E(t) is the silvicultural effort at time t, w is the per unit cost of the silvicultural effort, r is the rent of the forest land, δ is the continuous discount rate, and x_0 is the initial forest stock level. g(•) is the growth function of the forest stock, which is assumed to be continuous, twice differentiable, and strictly quasi-concave. These assumptions on the forest growth function seem reasonable because previous studies have shown that forest growth per unit area is generally a logistic or quadratic function of its stock (Smith 1962, Binkley and Dykstra 1987). For a unique interior optimum to exist, U(h) and V(x) are assumed to be continuous, twice differentiable, increasing, and quasi-concave in h and x, respectively. Some studies indicated that the nontimber benefit function V(x) may not be increasing or concave (Calish *et al.* 1978, Swallow *et al.* 1990). The violation of these two assumptions on V(x) may lead to multiple local optima, from which a global optimum can be identified, but will not affect the first-order necessary conditions for an optimum (local or global). Since this study focuses on the optimal solution and the impact of some economic and financial factors on the optimal steady-state solution, the violation of the increasingness and quasi-concavity of V(x) will not change the main results derived here.

Equation (1) is the objective function which maximizes the net timber and nontimber benefits over an infinite time period. Equation (2) is the forest stock constraint, which implies that the change rate of the forest stock is the difference between net natural growth and harvest. Equation (3) is the initial stock constraint. Inequality (4) is the nonnegativity constraint for the forest stock. Equations (1)–(3) and inequality (4) constitute an optimal control problem with one state variable x(t) and two control variables, h(t) and E(t). Its corresponding present-value Hamiltonian expression is:

(5) $H[x(t), h(t), E(t); \lambda(t)] = \{U[h(t)] + V[x(t)] - wE(t) - r\}e^{-\delta t} + \lambda(t)\{g[x(t), E(t)] - h(t)\}$

Here λ(t) is the costate variable, indicating the present-value shadow price of the forest stock (x). The current-value Hamiltonian expression can be written as:

(6) $\tilde{H}[x(t), h(t), E(t); \mu(t)] = U[h(t)] + V[x(t)] - wE(t) - r + \mu(t)\{g[x(t), E(t)] - h(t)\}$

$\mu(t) = \lambda(t)e^{\delta t}$ is the current-value shadow price of the forest stock (x). The first-order optimality conditions of this problem are given by:

(7) $\frac{\partial \tilde{H}}{\partial h} = U_h - \mu = 0$

(8) $\frac{\partial \tilde{H}}{\partial E} = -w + \mu g_E = 0$

(9) $\frac{d\mu}{dt} - \delta\mu = -\frac{\partial \tilde{H}}{\partial x} = -V_x - \mu g_x$

Reorganizing equations (7) and (8), we have:

(10) $U_h = \mu$

(11) $w = \mu g_E$

Equation (10) suggests that at the optimal harvest level, the marginal timber benefit must be equal to the current-value shadow price of the forest stock. Equation (11) implies that the demand for factor E should be determined by equalizing the price of the factor to the current value of its marginal product.

Equations (2), (3), (9), (10), and (11), along with inequality (4), constitute a simultaneous equation system. Given functions U(h), V(x), and g(·), and the values of w, δ, and x_0, the optimal paths (traparetrics) of the controls, h(t) and E(t), and state x(t) can be solved analytically or numerically. By setting $\frac{dx}{dt} = \frac{dh}{dt} = \frac{dE}{dt} = 0$, we can solve for the optimal equilibrium, the optimal steady-state solution (x*, h*, E*). For the detailed procedures regarding the solution of an optimal control problem, please refer to Clark (1990) and Conrad and Clark (1987).

OPTIMAL STEADY-STATE FOREST STOCK AND HARVEST

From the theoretical model presented previously, the optimal equilibrium levels of the forest stock and harvest can be derived. In addition to maximizing the present value of the net timber and nontimber benefits, the solution from the above model also represents a sustainable level of the forest stock and harvest because the optimal equilibrium is a steady-state solution. Therefore, the optimal steady-state forest stock and harvest are efficient and sustainable. Here we discuss two scenarios representing the consideration of (i) only the timber value, and (ii) both the timber and nontimber benefits.

Taking the time derivative of equation (10) and substituting it into equation (9) with U_h substituting for μ (equation (10)), we obtain:

(12) $\frac{dh}{dt} = \frac{U_h}{U_{hh}}(\delta - g_x) - \frac{V_x}{U_{hh}}$

At the equylibrium $\frac{dh}{dt} = 0$. Thus,

$$(13) \quad U_h(\delta - g_x) - V_x = 0$$

That is,

$$(14) \quad \delta = g_x + \frac{V_x}{U_h}$$

The variable g_x can be interpreted as the marginal growth of the forest stock, the change in the forest growth for each additional unit of its stock. Equation (14) suggests an important relationship among the discount rate, the marginal growth of the forest stock, and the ratio of the marginal nontimber benefit to the marginal timber benefit for the optimal steady-state forest stock and harvest. According to the equation, the optimal steady-state forest stock and harvest should be such that the discount rate is equal to the sum of the marginal growth of the forest stock and the ratio of the marginal nontimber benefit to the marginal timber benefit.

Consideration of Only Timber Value

If only timber is valued, $V_x = 0$. Since $U(\cdot)$ is increasing in h, equation (14) becomes:

$$(15) \quad \delta = g_x$$

Equation (15) implies that in order to maximize the timber benefit from forest harvests in the long run (at the steady state), we should maintain the forest stock at such a level that the marginal growth of the stock equals the discount rate. For a quasi-concave growth function $g(\cdot)$, there exists the following relationships between the forest stock (x) and the maximum sustainable yield (MSY) stock (x_{MSY}):

$$(16) \quad \begin{matrix} < & & > \\ x = x_{MSY}, & when & g_x = 0 \\ > & & < \end{matrix}$$

Hence, when the discount rate approaches zero, g_x also approaches zero, suggesting that the optimal steady-state stock and harvest are equal to the MSY stock and MSY, respectively. As long as the discount rate is positive, $g_x > 0$ at the steady state, indicating that with the consideration of only the timber value, the steady-state optimal forest stock and harvest are smaller than the MSY stock and MSY, respectively. If the forest stock (yield) can be considered to be positively related to its age, this is parallel to the result that the optimal rotation length is shorter than the age corresponding to MSY, founded by many studies on the optimal forest rotation (Bentley and Teeguarden 1965, Samuelson 1976, Hyde 1980, Chang 1983, Clark 1990).

Consideration of Both Timber and Nontimber Benefits

Rearranging equation (14), we have:

$$(17) \quad g_x = \delta - \frac{V_x}{U_h}$$

At the optimal equilibrium, g_x could be positive, negative, or zero. If $\delta < V_x/U_h$, or $\delta = 0$, then $g_x < 0$, indicating that the optimal forest stock exceeds the MSY stock, and that the corresponding optimal harvest is smaller than MSY for a quasi-concave $g(\cdot)$. If $\delta = V_x/U_h$, then $g_x = 0$, implying that optimal steady-state forest stock and harvest are equal to the MSY stock and MSY, respectively. If $\delta > V_x/U_h$, $g_x > 0$. In this situation, the optimal forest stock is smaller than the MSY stock. The optimal harvest is smaller than the MSY as well.

Since V(x) and U(h) are increasing in x and h respectively, i.e., V_x and U_h are positive, based on equation (17) we can infer:

$$(18) \quad \delta > g_x$$

The comparison of equation (15) with equation (18) indicates that at a given discount rate, the optimal steady-state forest stock when both timber and nontimber benefits are valued exceeds that when only the timber is valued. This result is true as long as the forest growth function $g(\cdot)$ is quasi-concave in stock (x). It is independent of the function forms of U(h) and V(x), which could be difficult to quantify (particularly V(x)). Previous studies on the determination of the optimal rotation length (Hartman 1976, van Kooten *et al.* 1995) showed that the rotation period with the consideration of both timber and nontimber benefits would be longer than that with the consideration of only the timber benefit. For a given area of forest land, a larger forest stock means an older stand as long as the forest stock is below its carrying capacity. Therefore, our result, when applied to even-aged forest plantations, is also consistent with these previous findings. Moreover, the optimal steady-state harvest level when both timber and nontimber benefits are valued is higher (lower) than that when only the timber benefit is considered if g_x valued at the optimal equilibrium is greater (less) than zero. Comparing equation (15) with equation (17) reveals that the effect of V_x/U_h and the discount rate on the optimal forest stock and harvest is of the same magnitude, but has opposite directions. In other words, inclusion of nontimber benefit in the determination of the optimal steady-state forest

stock and harvest is equivalent to reducing the discount rate by V_x/U_h.

AN EMPIRICAL EXAMPLE: U.S. CONIFEROUS FORESTS

The theoretical model and conclusions presented above are illustrated by using the western and eastern U.S. coniferous forests as an empirical example. In our theoretical model, the forest growth per unit area, g(x, E) is defined as a function of the forest stock (x) and silvicultural effort (E). Unfortunately, such a forest growth function is rarely available. For the simplicity of the illustration, let us assume that E is fixed. Thus, we consider forest growth as a function of its stock only. Binkley and Dykstra (1987) estimated such forest growth functions for major forests in the world. Their estimated forest growth functions for both the western and eastern U.S. coniferous forests are used for demonstration here. The growth models they estimated are:

- For the western U.S. coniferous forest:

(19) $g(x) = 0.0625x - 0.0002803x^2$

- For the eastern U.S. coniferous forest:

(20) $g(x) = 0.00493x^2 - 0.0001059x^3$

Equation (19) is a logistic function, and equation (20) is a cubic function. Both of them are continuous, twice differentiable, and strictly quasi-concave.

Assume that the timber benefit U(h) = ρh, and the nontimber benefit V(x) = ρx. Using equation (2) after dropping E(t) and equations (4), (7), and (9), we can solve for the optimal steady-state forest stock (x*) and harvest (h*) as follows:

- For the western U.S. coniferous forest:

(21) $$x^* = 1783.803\left(\frac{\rho}{p} - \delta + 0.0625\right)$$

(22) $$h^* = 1783.803\left(\frac{\rho}{p} - \delta + 0.0625\right)\left[0.0625 - 0.5\left(\frac{\rho}{p} - \delta + 0.0625\right)\right]$$

- For the eastern U.S. coniferous forest:

(23) $$x^* = 1573.812\left\{0.009862 + \left[0.000097259 - 0.00127176\left(\delta - \frac{\rho}{p}\right)\right]^{0.5}\right\}$$

(24) $$h^* = x^{*2}\left(0.004931 - 0.0001059x^*\right)$$

The optimal steady-state forest stock and harvest for the western and eastern U.S. coniferous forests under various levels of the ρ/p ratio and the discount rate (δ) according to equations (21), (22), (23), and (24) are shown in tables 1 and 2, respectively. These two tables suggest how much to cut and to remain in the long run (at the steady state) for one acre of the western and eastern conifers at a given discount rate and a specific ratio of the marginal nontimber benefit to the marginal timber benefit.

Based on the forest growth functions (equations (19) and (20)), the maximum forest stock (carrying capacity) is 222.98 m^3/ac (cubic meters per acre) for the western coniferous forests and 46.56 m^3/ac for the eastern coniferous forests. The maximum sustainable yield (MSY) and the MSY stock are respectively 3.48 m^3/ac/yr (cubic meters per acre per year) and 111.49 m^3/ac for the western conifers, and 1.58 m^3/ac/yr and 31.04 m^3/ac for the eastern conifers.

Tables 1 and 2 show that for both the western and eastern conifers, if nontimber benefit is not valued, the optimal steady-state stock levels are smaller than their MSY stocks, and the optimal steady-state harvest levels are also smaller than MSY. Also, without the consideration of nontimber benefit, the optimal steady-state forest stock and harvest decrease as the discount rate increases. As the discount rate approaches zero, the optimal steady-state stock and harvest approach the MSY stock and MSY, respectively. Inclusion of nontimber benefit increases the optimal steady-state stock at a specific discount rate. However, even with the consideration of nontimber benefit, the optimal steady-state stock and harvest can be smaller than, equal to, or larger than the MSY stock and MSY, respectively, depending upon the sign of ρ/p - δ. As long as ρ/p = δ, the optimal steady-state stock should be equal to the MSY stock and the optimal steady-state harvest should equal the MSY. When ρ/p > δ, the optimal steady-state harvest should be smaller than MSY, but the optimal steady-state stock should be maintained at a level larger than the MSY stock. If ρ/p is high enough relative to the discount rate, no timber should be harvested, and the forest stock will reach its carrying capacity. For example, at δ = 4 percent no timber should be harvested from the western U.S. coniferous forests if ρ/p m 0.12 (table 1), and from the eastern U.S. coniferous forests if ρ/p ≥ 0.28 (table 2). When ρ/p < δ , the optimal steady-state stock and harvest should be smaller than MSY and the MSY stock, respectively. On the other hand, if δ is high enough relative to ρ/p, the forests should be cleared. According to tables 1 and 2, if the nontimber benefit is not valued, both the western and eastern conifers would be cleared if the real continuous discount rate is 8 percent or higher. These two tables also illustrate that an increase in ρ/p is equivalent to deflating the discount rate by the same amount in terms of the impact on the optimal steady-state

stock and harvest. For any combinations of δ and ρ/p, as long as $\rho/p - \delta$ is equal to the same value, their corresponding steady-state forest stock and harvest are identical.

As described above, the optimal steady-state harvest is actually the long-run sustainable timber supply. If nontimber benefit is not valued, the western coniferous forest will supply 2.06 m^3/ac/yr of timber, and the eastern coniferous forest 1.48 m^3/ac/yr at a 4 percent real discount rate in the long run. The long-run timber supply levels (equal to h*) for the western and eastern U.S. coniferous forests at various ρ/p ratios and discount rates can be found in tables 1 and 2.

The current average annual timber removal is about 0.6 m^3/ac from the western coniferous forest and 1.4 m^3/ac from the eastern coniferous forest (Waddell *et al.* 1989). If the current state of these forests can be thought to be around their optimal steady states, the ρ/p ratio corresponding to the current timber removal level for either the western or eastern U.S. coniferous forests is approximately equal to 0.1 (tables 1 and 2). This implies that the nontimber benefit we valued is about 10 percent of the timber prices for both the western and eastern U.S. coniferous forests.

SUMMARY AND CONCLUSIONS

Information on how much to cut (harvest) and to remain (stock), like that on when to cut (rotation age), is important in forest management. Using forest stock and harvest levels as decision variables is applicable to the management of both plantations and natural forests. This paper describes an approach to determining the optimal forest stock and harvest and demonstrates the applicability of this approach in empirical forest management using the example of the U.S. coniferous forests. Our results indicate that the optimal steady-state forest stock increases when nontimber benefit is added to timber benefit. The optimal steady-state stock does not exceed the MSY stock when only timber is valued, but it can be smaller than, equal to, or larger than the MSY stock when both timber and nontimber benefits are valued. The impact of the inclusion of nontimber benefit on the optimal stock and harvest is the same as that of a decrease in the discount rate by the ratio of the marginal nontimber benefit to the marginal timber benefit (V_x/U_h). Too high a discount rate (relative to V_x/U_h) could lead to deforestation. A high value of V_x/U_h can help conserve forest resources.

The results from our empirical examples have several potential applications and implications. First, the optimal timber harvest levels in tables 1 and 2 can be used to project the long-run timber supply from the western and eastern U.S. coniferous forests. Second, the current timber removal level is close to its MSY in the eastern coniferous forest, but much below its MSY in the western coniferous forest. Therefore, the maximum sustainable yield is at least not the only criterion we currently use to manage the western conifers. Third, the ratio of the marginal nontimber benefit to the marginal timber benefit corresponding to the current timber removal level in both the eastern and western coniferous forests is around 0.1 at a 4 percent discount rate. Our current behavior in managing these forests implicitly reveals that the nontimber benefit of these conifers in general is valued at about 10 percent of their timber prices (the marginal timber benefit).

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Table 1. — *The optimal steady state forest stock (x*) and harvest (h*) per unit acre under various values of δ and ρ/p for the western U.S. coniferous forests*

	δ = 0%		δ = 2%		δ = 4%		δ = 6%		δ = 8%		δ = 10%	
ρ/p	x*	h*	x*	h*	x*	h*	x*	h*	x*	h*	x*	h*
0.000	111.488	3.484	75.812	3.127	40.136	2.057	4.460	0.273	0.000	0.000	0.000	0.000
0.010	129.326	3.395	93.650	3.395	57.974	2.681	22.298	1.254	0.000	0.000	0.000	0.000
0.020	147.164	3.127	111.488	3.484	75.812	3.127	40.136	2.057	4.460	0.273	0.000	0.000
0.030	165.002	2.681	129.326	3.395	93.650	3.395	57.974	2.681	22.298	1.254	0.000	0.000
0.040	182.840	2.057	147.164	3.127	111.488	3.484	75.812	3.127	40.136	2.057	4.460	0.273
0.050	200.678	1.254	165.002	2.681	129.326	3.395	93.650	3.395	57.974	2.681	22.298	1.254
0.060	218.516	0.273	182.840	2.057	147.164	3.127	111.488	3.484	75.812	3.127	40.136	2.057
0.070	222.975	0.000	200.678	1.254	165.002	2.681	129.326	3.395	93.650	3.395	57.974	2.681
0.080	222.975	0.000	218.516	0.273	182.840	2.057	147.164	3.127	111.488	3.484	75.812	3.127
0.090	222.975	0.000	222.975	0.000	200.678	1.254	165.002	2.681	129.326	3.395	93.650	3.395
0.100	222.975	0.000	222.975	0.000	218.516	0.273	182.840	2.057	147.164	3.127	111.488	3.484
0.150	222.975	0.000	222.975	0.000	222.975	0.000	222.975	0.000	222.975	0.000	200.678	1.254
0.200	222.975	0.000	222.975	0.000	222.975	0.000	222.975	0.000	222.975	0.000	222.975	0.000

Note: The growth model of the western U.S. coniferous forests is from Binkley and Dykstra (1987). The units of x* and h* are m^3/acre and m^3/acre/year, respectively.

Table 2. —*The optimal steady state forest stock (x*) and harvest (h*) per unit acre under various values of δ and ρ/p for the eastern U.S. coniferous forests*

	δ= 0%		δ = 2%		δ = 4%		δ = 6%		δ = 8%		δ = 10%	
ρ /p	x*	h*	x*	h*	x*	h*	x*	h*	x*	h*	x*	h*
0.00	31.042	1.584	28.859	1.561	26.240	1.482	22.725	1.304	0.000	0.000	0.000	0.000
0.01	32.025	1.579	29.992	1.579	27.620	1.530	24.653	1.410	20.037	1.128	0.000	0.000
0.02	32.954	1.565	31.042	1.584	28.859	1.561	26.240	1.482	22.725	1.304	0.000	0.000
0.03	33.835	1.543	32.025	1.579	29.992	1.579	27.620	1.530	24.653	1.410	20.037	1.128
0.04	34.676	1.514	32.954	1.565	31.042	1.584	28.859	1.561	26.240	1.482	22.725	1.304
0.05	35.481	1.477	33.835	1.543	32.025	1.579	29.992	1.579	27.620	1.530	24.653	1.410
0.06	36.255	1.435	34.676	1.514	32.954	1.565	31.042	1.584	28.859	1.561	26.240	1.482
0.07	37.001	1.386	35.481	1.477	33.835	1.543	32.025	1.579	29.992	1.579	27.620	1.530
0.08	37.722	1.332	36.255	1.435	34.676	1.514	32.954	1.565	31.042	1.584	28.859	1.561
0.09	38.421	1.273	37.001	1.386	35.481	1.477	33.835	1.543	32.025	1.579	29.992	1.579
0.10	39.098	1.208	37.722	1.332	36.255	1.435	34.676	1.514	32.954	1.565	31.042	1.584
0.15	42.230	0.818	41.024	0.987	39.757	1.139	38.421	1.273	37.001	1.386	35.481	1.477
0.20	45.032	0.329	43.945	0.535	42.814	0.728	41.634	0.905	40.399	1.065	39.098	1.208
0.25	46.563	0.000	46.563	0.000	45.561	0.220	44.493	0.434	43.385	0.633	42.230	0.818
0.30	46.563	0.000	46.563	0.000	46.563	0.000	46.563	0.000	46.081	0.108	45.032	0.329
0.35	46.563	0.000	46.563	0.000	46.563	0.000	46.563	0.000	46.563	0.000	46.563	0.000

Note: The growth model of the eastern U.S. coniferous forests is from Binkley and Dykstra (1987). The units of x* and h* are m^3/acre and m^3/acre/year, respectively.

A COMPARISON OF TWO GROWTH MODELS DEVELOPED FOR REGIONAL TIMBER INVENTORY PROJECTION

Marc McDill[1]

ABSTRACT.—This paper compares the inventory growth components of two timber supply models: STRIPS and RxWrite. STRIPS uses a plot-level growth model, and RxWrite uses a tree-level growth model. Both models were developed with USDA Forest Inventory and Analysis (FIA) data for Louisiana. They were calibrated by projecting undisturbed plots from the 1984 survey to 1991. Projected plot data were compared to the observed 1991 plot data. The models' plot volume root mean squared prediction errors are compared for six forest types and four species groups. In almost all cases, the STRIPS model performed better than the RxWrite model.

INTRODUCTION

Projecting regional timber inventories requires the prediction of three fundamental types of change: growth, removals, and area change. This paper focuses on the components that predict inventory growth for two timber supply models: STRIPS and RxWrite. The starting point, of course, for any inventory projection system is the current forest inventory. The primary source of regional timber inventory data in the U.S. is the USDA Forest Service's Forest Inventory and Analysis (FIA) data. In addition to providing starting inventory information, FIA data were used to develop the growth models discussed here. The FIA survey was not designed with this purpose in mind, and, consequently, there are many disadvantages to using FIA data for fitting growth models. In spite of this, FIA data have one key redeeming quality which makes them especially useful for this purpose: only the FIA data are representative of all conditions found in a region. Generally, growth models are developed using data from research plots, which are typically on public or industry land. Because of this selection bias, most growth models tend to over-predict growth on the average forest property—especially non-industrial private properties. Using FIA data to develop growth models eliminates this source of bias. In addition, while FIA data sets tend to be very noisy, they also are usually quite large, which helps to make up somewhat for what they lack in quality.

The objective of this study was to compare how well the two growth models predict the future characteristics of undisturbed FIA plots based on the characteristics of those plots today. STRIPS uses a plot-level growth model, and RxWrite uses a tree-level growth model. The models were fitted with data from the 1974, 1984, and 1991 FIA surveys of Louisiana. They were then calibrated by projecting undisturbed plots from the 1984 survey to 1991 and comparing the results to the actual plot data observed in 1991. Calibration parameters are iteratively re-estimated until the models provide unbiased predictions of a selected set of plot and/or tree characteristics. After calibration, the models were compared by calculating the root mean square errors of their predictions of plot volume by forest type and species group.

THE TIMBER SUPPLY MODELS

STRIPS

The growth models compared here were developed as part of two very different timber supply models. The first, STRIPS (Tucker and McDill 1996), projects the volume of growing stock[2] in four species groups on individual FIA plots. STRIPS uses plot-level growth equations to predict annual growth, which it adds each year to the existing volume on the plot in each of four species groups. STRIPS uses 22 growth equations—for each of 6 forest types, 3 to 4 models were developed to predict the growth in each species group found on that forest type. Removals are modeled as clearcuts or partial harvests of plots using historical harvest proportions estimated from the most recent forest survey cycle. These historical harvest proportions are adjusted up or down by a fixed amount so that the resulting harvest matches an

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[2] *A two-product version of STRIPS that projects both growing stock and sawtimber has been developed, but only the one-product model is discussed here.*

exogenously specified total removals target for each year. Changes in the total area of forest land are simulated by adjusting the area expansion factors associated with each plot. Area shifts among forest types are accomplished with Markovian transition matrices estimated from the most recent forest survey cycle. Four transition matrices are constructed for (1) clearcut plots, (2) partially harvested plots, (3) undisturbed plots with less than 500 ft^3/ac, and (4) undisturbed plots with more than 500 ft^3/ac.

RxWrite/GISTran/DTran

The second timber supply model, the RxWrite/GISTran/DTran system (Rose *et al.* 1992; McDill 1992, 1993), projects the state of the forest by choosing management alternatives for each FIA plot to minimize the cost of meeting projected mill requirements. Growth and removals are determined by the management alternative that is selected for each plot by the optimization algorithm. Similarly, forest type change is determined through the selection of regeneration options for each plot. Unlike STRIPS, in the RxWrite/GISTran/DTran system it is only possible for the forest type of a plot to change when the plot is clearcut. RxWrite is a prescription simulator used to develop management alternatives for the system. RxWrite was originally developed for the Lake States and was written to use STEMS (Belcher 1981, Brand 1981) to model plot growth. Because STEMS is a tree-level growth model, RxWrite is able to model a variety of thinning and product merchandizing options. A tree-level growth model was developed for Louisiana to retain these advantages in the Southern version of RxWrite.

THE GROWTH MODELS

Strips

As discussed earlier, STRIPS uses three to four growth models for each forest type—one for each species group found on that forest type. The four species groups are: pine, cypress, soft hardwoods, and hard hardwoods. The six forest types are: longleaf/slash pine, loblolly/shortleaf pine, oak-pine, oak-hickory, oak-gum-cypress, and elm-ash-cottonwood. No cypress volume occurs on longleaf/slash pine types, and no pine occurs on elm-ash-cottonwood. The annual growth in each species group is modeled as a function of the total volume on the plot, the volume on the plot of the particular species group being modeled, the site class, and the plot ownership (public, industry, or non-industrial private) and origin (planted or natural—only used on pine and oak-pine types). The general model form is:

where Vol_t = the total volume on the plot;
Vol_i = the volume on the plot in species group i;
S = the plot site class[3];
Org = a dummy variable set to 1 if the plot is planted (only used on pine and oak-pine);
Pub = a dummy variable set to 1 if the plot is on publicly-owned land; and
Ind = a dummy variable set to 1 if the plot is on land owned by forest industry.

$$\Delta Vol_i = B_0 + B_1 Vol_t + B_2 Vol_t^2 + B_3 Vol_i + B_4 Vol_i^2 + B_5 S + B_6 Org + B_7 Pub + B_8 Ind + B_9 Org\ Vol_t + B_{10} Pub\ Vol_t + B_{11} Ind\ Vol_t + B_{12} Org\ Vol_i + B_{13} Pub\ Vol_i + B_{14} Ind\ Vol_i$$

Equation (1) was fitted to data from undisturbed FIA plots from the 1974-1984 and 1984-1991 survey cycles of Louisiana. A backward stepwise procedure was used to find the best model with all parameter estimates significant at least at the 0.10 level of significance. It is notable that site class was not a significant variable in the majority of cases, and most of the time when site was significant, the coefficient was negative. When the site coefficient was negative, site class was removed from the equation. Space limitations prevent listing the coefficients and their standard errors for all 22 equations. Table 1 shows the number of observations and the r-squared for each model. The r-squares were low, ranging from as low as 0.033 to 0.535.

RxWrite

The state of a tree in the RxWrite database is described by its species, height, diameter (DBH), and crown ratio. Also associated with each tree record is an expansion factor, which indicates the number of trees per acre represented by the tree. Projection equations are needed for each of these attributes (except species). In RxWrite, height and DBH are projected with growth equations, crown ratio is projected with a change equation, and the tree expansion factor is projected with a mortality equation. In addition, height and crown ratio were not available for trees with a DBH less than 5 inches. Therefore, height and crown ratio models were developed to predict initial values for these attributes. Due to space limitations, those models are not discussed further here.

In order to be useful for projections, the prediction equations had to use only tree and plot-level variables that would be projected by the system. The available set of predictor variables was:

[3] *The site class variable in the FIA data is coded with 1 for the best sites and 7 for the worst sites. The variable used here is eight minus the FIA site class variable so that higher values will indicate better sites.*

Table 1.—*STRIPS growth model r-squares*

Forest Type	Number of observations	Pine	Cypress	Soft hardwood	Hard hardwood
Longleaf/Slash pine	119	0.149	n.a.	0.377	0.535
Loblolly/Shortleaf pine	1,070	0.197	0.300	0.170	0.344
Oak-Pine	573	0.071	0.033	0.089	0.168
Oak-Hickory	614	0.110	0.163	0.212	0.167
Oak-Gum-Cypress	2,368	0.270	0.202	0.107	0.201
Elm-Ash-Cottonwood	205	n.a.	0.464	0.128	0.488

– tree variables: species (Spp), height (Ht), diameter (DBH), and crown ratio (CR);
– plot variables: site class (S) and basal area (BA);
– tree/plot variable: tree diameter over the plot quadratic mean diameter (DOQ).

Height and crown ratio were not measured in 1974, so only data from the 1984-1991 survey cycle were used to fit the RxWrite model. The general form of the four tree development equations are:

$$\Delta Ht = f(Ht, DBH, CR, S, BA, DOQ)$$

$$\Delta DBH = f(Ht, DBH, CR, S, BA, DOQ)$$

$$\Delta CR = f(Ht, DBH, CR, S, BA, DOQ)$$

$$Prob(Mortality) = f(Ht, DBH, CR, S, BA, DOQ)$$

These equations were estimated for 18 species groups. The specific model forms used in these equations varied from one species group to another and cannot be described here due to space limits. Both linear and nonlinear models were used. Table 2 lists the species groups and the number of observations and r-squares of each model. In general, the r-squares are low, which should not be surprising, given the use of different data and the noisy nature of FIA data. Surprisingly, the r-squares tended to be highest for the crown ratio change models. The mortality models are logit models, and the r-square has a different interpretation for those models. Roughly speaking, it represents the increase in the proportion of correct predictions with the fitted model as compared with a naive model with no explanatory variables. As with the STRIPS growth model, site class was seldom a good predictor of tree growth.

Table 2.—*RxWrite growth model r-squares*

Species group	Number of observations	Height	Diameter	Crown ratio	Number of observatioms	Mortality
Slash/Longleaf pine	714	0.160	0.298	0.457	167	0.160
Loblolly pine	3,353	0.304	0.421	0.526	1,993	0.041
Shortleaf/Spruce pine	535	0.040	0.308	0.310	325	0.104
Baldcypress	707	0.043	0.080	0.460	1,302	0.043
Red cedar	6	0.855	0.873	0.999	4	n.a.
Tupelo	381	0.078	0.146	0.503	1,201	0.068
Gums/Yellow-poplar	1,143	0.070	0.123	0.385	1,143	0.034
Willow/Box elder/Sweetbay [a]	331	0.111	0.403	0.381		
Willow					434	0.134
Box elder and River birch					100	0.423
Sweetbay, etc.					169	0.280
Red Maple/Sugarberry/Elm	702	0.062	0.258	0.445	1,289	0.091
Oak Group 1	679	0.070	0.094	0.309	897	0.029
Oak Group 2	1,367	0.083	0.158	0.344	1,472	0.029
Water Hickory/ Dogwood/Persimmon	225	0.207	0.542	0.488	453	0.118
Hickory/Pecan	173	0.313	0.135	0.310	219	0.179
Beech	142	0.237	0.528	0.548	183	0.106
Ash/Walnut	269	0.209	0.239	0.407	588	0.127
General noncommercial	160	0.174	0.304	0.257	332	0.096

[a] Separate mortality models were fit for each sub-group within this species group.

CALIBRATION

It is an eye-opening exercise to project the state of permanent plots from one measurement to a later remeasurement using a growth model that has been fit statistically with data from those very plots. Without calibration, the models will typically produce biased estimates of the plot characteristics of the remeasured plots. This was the case with the models discussed here. As an example, the uncalibrated STRIPS model underprojected the volume on loblolly/shortleaf pine plots. Calibration parameters can be used to either increase or decrease the change in specific plot or tree attributes over the projection so that the model produces unbiased projections of those attributes. For example, in STRIPS each growth estimate for pine on loblolly/shortleaf pine plots can be multiplied by some constant, say 1.1, to increase the projected volume of pine on loblolly/shortleaf pine plots at the end of the projection. The appropriate values for these calibration parameters were calculated by repeatedly projecting plot data for undisturbed plots from 1984 to 1991 and comparing the characteristics of the projected plot and tree data with the observed characteristics of those plots in 1991. The calibration parameters are re-estimated iteratively until the projected values of these selected plot characteristics are unbiased. Newton's method, with some modifications, was used to re-estimate the calibration parameters.

STRIPS

In STRIPS, all of the calibration parameters are multiplicative; i.e., growth estimates for a given forest type and species group are multiplied by the calibration parameter for that forest type and species group. If a model needs no adjustment (an unlikely possibility), the calibration parameter will be 1; i.e., the "null value" of the parameter is 1. The calibration parameters are re-estimated until the average difference between the projected plot volumes and the actual plot volume is 0 for each species group and forest type. Table 3 shows the values of the STRIPS calibration parameters for Louisiana 1984-1991. The values typically are quite different from 1. The values range from 0.1 (the minimum value allowed) for cypress growth on oak-pine plots to 4.0 (the maximum value allowed) for cypress growth on oak-hickory plots. The calibration parameter values are greater than one more often than they are less than one.

RXWRITE

The RXWRITE growth model uses 5 calibration parameters for each of 56 species groups (a total of 280 parameters). Each of the height, diameter, and crown ratio models are adjusted with one parameter. Two parameters are used to adjust the mortality model. The height growth and diameter growth model calibration parameters are multiplicative. The calibration parameters for those models are re-estimated until the average height and diameter prediction errors, for trees where a matching record exists in both the projected and the actual tree lists, are zero. Unlike the predicted height or diameter growth, the change in the crown ratio may be either positive or negative. In this case, a multiplicative calibration parameter will have unpredictable results—increasing both positive and negative changes. Thus, an additive calibration parameter was used with the RXWRITE crown ratio change model. A constant (positive or negative) value is added to each predicted crown ratio change. In calibrating the crown ratio change model, the objective was to eliminate the average difference between the predicted crown ratio and the actual crown ratio for tree records found in both the projected and actual tree lists.

Predicted mortality was calibrated using a multiplicative calibration parameter that is a negative exponential function of diameter. This calibration parameter was actually multiplied by the probability of survival, rather than the probability of mortality. The resulting probability of survival can potentially be greater than one. This partially compensates for the lack of an ingrowth model in the system. The tree expansion factor (the number of trees per acre represented by the tree record) is multiplied by this probability of surviving. Equation (6) illustrates this, showing how the tree expansion factor for tree i in period $t+1$ is calculated:

$$TrExp_{t+1,\,i} = k\, e^{-a\,DBH} \times [1 - P(mort)_{t,\,i}] \times TrExp_{t,\,i}$$

Table 3.—*STRIPS model calibration parameters*

Forest type	Pine	Cypress	Soft hardwood	Hard hardwood
Longleaf/Slash pine	1.47	n.a.	3.31	3.40
Loblolly/Shortleaf pine	1.64	2.00	2.01	1.54
Oak-Pine	1.45	0.10	1.75	1.41
Oak-Hickory	0.57	4.00	0.99	1.19
Oak-Gum-Cypress	1.12	1.37	1.08	0.74
Elm-Ash-Cottonwood	n.a.	0.83	0.65	1.03

Here, k and a are the calibration parameters for the mortality function. (Note: k can be considered the intercept and a the slope of the negative exponential.) *P(mort)* is the probability of mortality for the tree, given by Equation (5). The objective in searching for values of k and a for Equation (6) is to match the quadratic mean diameter and the number of trees for all trees in a given calibration species group in the set of plots used for calibration.[4]

As mentioned earlier, 56 species groups were used for calibration. This was done to try to correct for possible mis-aggregation of species in the 18 species groups used for statistical model development. In retrospect, 56 species groups was probably too many, but time limitations prevented us from re-doing the calibration with a smaller number of calibration species groups. Space limits prevent reporting all of the calibration parameter values calculated for the RxWrite model. Table 4 summarizes the calibration parameters for RxWrite by giving average parameter values for the four major species groups recognized by STRIPS.

Table 4.—*Average calibration parameters for RxWrite for four species groups*

Model	Pine	Cypress	Soft hardwood	Hard hardwood
Ht	1.077	2.511	0.931	0.994
DBH	1.196	2.500	1.517	2.209
CR	0.0005	0.0104	-0.0010	0.0083
Int. (k)	1.219	1.208	1.235	1.377
Slope (a)	0.0168	0.0084	0.0229	0.0268

MODEL COMPARISON

After the models were calibrated, they were compared to determine which one best predicted the actual volume on each plot. To make this comparison, the standard deviation of the difference between the projected volume in each species group was calculated for each forest type. Let

$$Err_{sg,\,p} = \hat{Vol}_{sg,\,p} - Vol_{sg,\,p}$$

where $Err_{sg,\,p}$ = the prediction error for species group sg on plot p,
$Vol_{sg,\,p}$ = the observed (no hat) or projected (^) volume in species group sg on plot p.

A model produces unbiased volume projections if the expected value of $Err_{sg,\,p}$ is zero. Note that the STRIPS model was specifically calibrated so that the average value of $Err_{sg,\,p}$ is zero for the set of calibration plots, but there is no guarantee that this will be the case with the RxWrite model. One would hope that if, on average, the number of trees on each plot is correct and the quadratic mean diameter is correct, then the average volume prediction would be nearly unbiased. The average prediction error for the RxWrite model is reported in the tables below, and the reader can judge whether this was the case. A model does a better job of projecting plot volume when the standard deviation of $Err_{sg,\,p}$ is smaller.

Tables 5 through 8 show the results of this evaluation of the different models by forest type for each of the four species groups recognized by RxWrite. For RxWrite, the average error (bias) is also reported. The tables also show the average volumes per acre for each species group on each forest type. This value provides a reference against which the relative size of the average deviations can be judged. In almost every case, the STRIPS growth model outperformed the RxWrite growth model. Typically, the average RxWrite errors are 50 to 100 percent larger than the average STRIPS errors. In spite of the general superiority of the STRIPS model relative to the RxWrite model, the average prediction errors of the STRIPS model are still uncomfortably high. This probably reflects the inherent poor quality, or noisiness, of the FIA data, and the problems of using these data for growth model development.

CONCLUSIONS

To the best of my knowledge, this is the first time a tree-level growth model and a plot-level (or stand-level) growth model have been developed and compared against each other using the same data set. In general, the fit statistics of the models were not good; r-squares were low. This is partly explained by the unavailability or poor quality of variables generally considered useful—some would say essential—for predicting growth and yield: age and site quality. In addition, FIA data are inherently noisy, representing a variety of very heterogeneous conditions. The uncalibrated models showed considerable bias, even when used to project the very data set with which they were developed. The calibration procedures applied with these models also are a unique feature of this study. The calibration parameters diverged considerably from their null values, reflecting the biases in the uncalibrated models. The final measures of the model errors showed that neither model predicts the

[4] *Note the difference between the set of trees used to calibrate the height, diameter, and crown ratio models and the set used to calibrate the mortality model. For the first three models, only trees with a matching record in both the projected and the observed tree lists are used, and each tree record is given a weight of 1. All trees are used for calibrating the mortality model, and they are weighted according to their expansion factors.*

future volume of FIA plots particularly well. All of this highlights the difficulties of projecting the state of FIA plots.

The results clearly demonstrate that the simpler plot-level model is better than the more complex tree level model. Of course, the comparison was made on the basis of the plot attributes that STRIPS is designed to project. Also, the STRIPS growth had the advantage of being fitted to data from two survey cycles (1974-1984 and 1984-1991), while the RxWrite model was fitted with data from only one survey cycle (1984-1991). In any case, the tree level model developed for RxWrite provides a wealth of additional detail in the projected plot data than the plot-level STRIPS model. If this additional detail is needed, then the tree-level model is obviously superior, in spite of its problems.

The results of this study likely will not surprise too many readers. They bear out the general principal that simpler models perform better than more complex models, and that additional complexity is generally only useful in a model if the additional detail provided by the model addresses some critical aspect of the process being modeled.

Table 5.—*Model comparison for pine (all values are cu. ft. per acre)*

Forest type	Average volume per acre	STRIPS standard deviation	RxWrite	
			Average error	Standard deviation
Longleaf/Slash pine	1757.44	593.29	104.78	771.2
Loblolly/Shortleaf pine	2027.89	620.14	-3.08	806.28
Oak-Pine	1138.83	467.21	-155.88	711.91
Oak-Hickory	345.37	287.41	39.37	506.36
Oak-Gum-Cypress	33.19	62.74	-8.57	117.56

Table 6. —*Model comparison for cypress (all values are cu. ft. per acre)*

Forest type	Average volume per acre	STRIPS standard deviation	RxWrite	
			Average error	Standard deviation
Loblolly/Shortleaf pine	3.19	15.99	-1.29	10.7
Oak-Pine	8.04	10.14	1.79	24.37
Oak-Hickory	39.08	127.24	2.34	69.93
Oak-Gum-Cypress	438.4	319.51	4.47	388.44
Elm-Ash-Cottonwood	137.85	76.01	-15.43	121.96

Table 7.—*Model comparison for soft hardwood (all values are cu. ft. per acre)*

Forest type	Average volume per acre	STRIPS standard deviation	RxWrite	
			Average error	Standard deviation
Longleaf/Slash pine	114.51	213.78	-22.84	117.64
Loblolly/Shortleaf pine	231.68	156.33	42.22	192.71
Oak-Pine	482.63	176.62	21.27	301.64
Oak-Hickory	572.79	199.26	-28.90	300.37
Oak-Gum-Cypress	1,028.95	362.30	-111.67	551.80
Elm-Ash-Cottonwood	1,502.88	618.21	133.27	1,045.78

Table 8.—*Model comparison for hard hardwood (all values are cu. ft. per acre)*

Forest type	Average volume per acre	STRIPS standard deviation	RxWrite	
			Average error	Standard deviation
Longleaf/Slash Pine	66.38	87.44	-42.39	102.35
Loblolly/Shortleaf Pine	301.76	211.44	9.81	237.04
Oak-Pine	702.23	245.72	-24.75	499.49
Oak-Hickory	1,034.64	308.92	-110.90	638.96
Oak-Gum-Cypress	837.62	285.22	-66.64	735.95
Elm-Ash-Cottonwood	306.77	278.07	-199.82	423.95

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EXPLORING ENHANCEMENTS TO DYNAMIC PROGRAMMING

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ABSTRACT.—Dynamic programming (DP) has long been used to solve the optimal rotation length and density problem in timber management. Recent modifications or enhancements to standard forward recursive DP include using "look-aheads," where future growth potential as well as current state values are compared explicitly to determine the optimal network path. The use of such look-aheads to completely solve one stage of the DP problem at a time has also been considered and is known as the PATH algorithm. DP has also been enhanced through the use of heuristics where state coefficients and entering state variable values are used to modify the objective function value in an attempt to favor stand attributes that are known to produce high-value rotations. This research will compare standard forward recursive DP to "look-ahead" assisted DP, heuristics-aided DP, and a PATH algorithm. The platform for comparison will be a forward-recursive DP model utilizing an individual-tree growth projection system. Criteria for comparison include required size of network formulation, objective function values, and required solution time.

INTRODUCTION

Dynamic programming (DP) has long been used to solve the optimal rotation length and density problem in forest management (Amidon and Akin 1968, Schreuder 1971, Haight *et al.* 1985). However, DP formulations become intractable in size quickly due to the use of multiple, continuous state variables (Brodie and Kao 1979, Arthaud 1986). Several methods of "enhancing" DP formulations have been made to DP and will be discussed briefly below.

The first enhancement to DP is the use of "neighborhood storage" (Brodie and Kao 1979). This involves converting continuous state variables into state "neighborhoods" in which all entering states are considered the same in terms of future growth potential. Then only the state with the highest accumulated value is maintained. The formulation for this method is shown below:

(1) $$f_N(Y_N) = \sum_{n=0}^{N} r_n(T_n)$$

(2) $$Y_n + G_{n+1}(Yn) - T_n + Y_{n+1}(n = 0,1,2,....,N - 1)$$

(3) $$X_N - T_N = 0$$

(4) $$f_n(Y_n) = \max_{Y_{n-1}, T_n} [r_n(X_n, T_n) + f_{n-1}(Y_{n-1})]$$

Equation 4 is the standard forward recursive DP equation that is used. Y_{n-1} represents a state vector that can be modeled by discrete states or continuous states or state neighborhoods as is the case in this study.

Paredes and Brodie (1987) and Yoshimoto *et al.* (1990) suggested that a growth look-ahead might be used to explicitly determine the value of all future growth from a particular state. Using a growth look-ahead to augment the DP formulation would change the recursive equation (4) to:

(5) $$f_n(Y_n) = \max_{Y_{n-1}, T_n} [r_n(X_n, T_n) + r_L G_L(Y_n) + f_n\text{-}1(Y_{n-1})]$$

In equation 5, each state (Y_n) is projected forward L years by the function $G_L(Y_n)$ and a return function r_L converts this growth to volume and value. Thus, the accumulated value plus the explicit projected value of the

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state entering a neighborhood is compared to the highest current value occupying the neighborhood with the highest value being retained.

Paredes and Brodie (1987) suggested that if the growth function is monotonically increasing, then an entire stage can be solved at once using the growth look-ahead and changing the recursive relationship to:

$$(6)\quad f_n(Y_n) = \max_{T_n} [r_n(X_n, T_n) + r_L G_L(Y_n) + f_{n-1}(Y_{n-1})]$$

In this case, only the highest value state in each stage is saved for projection in future stages, under the assumption that the growth projection provides enough information about the future value of all states in a stage that the optimal can be chosen.

The final enhancement to DP is the use of heuristics (Arthaud and Pelkki 1996). The process is very similar to the growth look-ahead, but instead of a growth function, a simple heuristic equation is used to augment the accumulated value and favor certain intra-state conditions. The recursive relationship and heuristic equation used in this study are:

$$(7)\quad f_n(Y_n) = \max_{Y_{n-1}, T_n} [r_n(X_n, T_n) + H(Y_n) + f_{n-1}(Y_n\text{-}1)]$$

The coefficients (b_1 and b_2) can weigh intrastate conditions with higher average diameter (DBH) and number of trees (NT) as the user desires.

$$(8)\quad H(Y_n) = b_1(\overline{DBH}) + b_2(NT)$$

This study examines each of these techniques on a single problem formulation and evaluates them in terms of objective function value found and memory and processing time requirements.

METHODS AND DATA

The DP and enhanced DP simulations were completed on a hypothetical yellow poplar stand. The objective function of all simulations was to maximize soil expectation value. The stand input data was derived from regional diameter distributions for a 20-year-old site of yellow poplar with an index of 110 (Knoebel *et al.* 1986, McGee and Della-Bianca 1967). This data was selected because the growth projection system used is based on the GROW subroutine (Brand 1981) with northeast regional parameters (Yaussy and Gale 1992). Tree quality projections were made according to the methods in Yaussy (1993) with regional tree quality averages coming from the Eastwide Forest Inventory Database (Hansen *et al.* 1992). As stated, a forward recursive DP algorithm was employed with a stage interval of 2 years.

Five different thinning types (above, below, above and below, improvement, and high-grade) were included with removal intensities running from 10-50 percent in 5 percent increments in all simulations. An $80 per acre fixed entry cost was charged on all harvest entries and thinning revenue was penalized 15 percent for variable thinning costs. Stumpage prices for roundwood and sawtimber by grade were derived from regional price reports. A 4 percent real rate of return was used as the cost of capital in all simulations.

All combinations of two-state parameter DP simulations were tested using the state variables of basal area (BA), number of trees (NT), cubic foot volume (VOL), and average diameter (DBH). These two-state DP models were tested with various state neighborhood sizes to observe improvements in the objective function value with decreases in state neighborhood size.

Once the DP simulations were completed, a known suboptimal state neighborhood combination was tested with the DP+look-ahead formulation. This was done to see if any of the enhancements to DP could make up for state neighborhoods that definitely violated the principle of optimality. Also, it was desirable to start with state neighborhoods that were large and resulted in very fast DP solution times since many runs would be tested. First, various lengths of growth look-ahead were tested to see which, if any, produced the best results. Then the best growth look-ahead was used with a variety of DP state neighborhood combinations to see how much the objective function value could be improved.

The next step was to apply the PATH algorithm. As mentioned above, PATH retains only one state per stage. The state retained is the one with the highest accumulated and future growth value. Therefore, state neighborhood size is immaterial, and several growth look-ahead periods were evaluated to see how PATH compared to other methods.

The final DP enhancement tested was DP+heuristic. As shown above, a simple heuristic was tested by using a binary search to find heuristic parameters (b_1 and b_2) that would improve the DP formulation. The DP+heuristic was tested in the same manner as the DP+look-ahead.

RESULTS AND DISCUSSION

Out of the six combinations of state variables, only the results from BA-VOL and DBH-NT are shown due to space limitations. Tables 1 and 2 depict results for BA-VOL and DBH-NT, respectively. The best objective

function value found in any state neighborhood combination was $326.2, although as indicated in table 2, not every combination was able to find this solution. In general, as state neighborhood size decreases, the objective function value increases. The state neighborhood combination of DBH = 0.5" and NT = 5 trees per acre was selected for testing the DP+look-ahead and DP+heuristic enhancements.

Table 1.—*Results of DP only simulations with various basal area (BA) and cubic foot volume per acre (VOL) state neighborhoods*

BA state neighborhood (inches)	Cubic foot volume per acre state neighborhood				
	6	10	20	40	80
0.1	insuff. memory	insuff. memory	**324.7**[a] *452301*[b]	**324.4** *226926*	**320.8** *115264*
0.2	**326.2** *752335*	**324.7** *451401*	**324.4** *226151*	**324.4** *113525*	**311.0** *57664*
0.5	**322.9** *301435*	**322.9** *180861*	**322.0** *90611*	**311.0** *45486*	**311.0** *23104*
1.0	**324.4** *151135*	**322.0** *90861*	**322.0** *45431*	**322.0** *22806*	**280.5** *11584*
2.0	**322.0** *75985*	**322.0** *45591*	**322.0** *22841*	**322.0** *11466*	**283.1** *5824*

[a]Figures in bold are objective function values (Soil Expectation Value (SEV) in $/ac).
[b]Figures in italics are the numbers of state neighborhoods required per stage.

Table 2.—*Results of DP only simulations with various average diameter (DBH) and number of trees per acre state neighborhoods*

DBH state neighborhood (inches)	Number of trees per acre state neighborhood				
	1	2	5	10	20
0.1	**313.5**[a] *180851*[b]	**313.5** *90651*	**310.3** *36531*	**294.2** *18491*	**294.2** *9471*
0.2	**320.5** *90626*	**320.5** *45426*	**294.2** *18306*	**278.2** *9266*	**278.2** *4746*
0.5	**310.3** *36491*	**310.3** *18291*	**281.4** *7371*	**278.9** *3731*	**270.6** *1911*
1.0	**287.0** *18446*	**292.6** *9246*	**278.2** *3726*	**278.2** *1886*	**249.0** *966*
2.0	**278.2** *9746*	**278.2** *4824*	**278.2** *1944*	**278.2** *984*	**238.4** *504*

[a]Figures in bold are objective function values (Soil Expectation Value (SEV) in $/ac).
[b]Figures in italics are number of state neighborhoods required per stage.

Table 3 shows various growth look-ahead lengths applied to the basic DP formulation. From this it is obvious that the look-ahead is of tremendous value and explicit calculation of stand value improves upon DP solutions with much smaller state neighborhoods. However, very long projections of 20, while improving upon a suboptimal DP formulation, do not yield an objective function as high as DP alone.

Table 3.—*Testing various look-ahead periods on DP state neighborhoods where DBH=0.5 inches and NT = 5/ac*

Look-ahead period	Objective function value	Time to complete	Number of required stages
	$/acre	*seconds*	
NONE (DP only)	281.4	3450	26
0	327.2	6373	40
1	327.1	7377	40
2	329.3	8069	36
5	329.3	7931	36
10	329.0	9362	35
20	324.6	14047	40

The results of taking the optimal look-ahead period of 5 years and applying it to various state neighborhood sizes is shown in table 4. The growth projection requires two to three times more processing time but no additional memory, and all DP+look-ahead combinations are better than DP alone. Most importantly, the DP+look-ahead finds a higher valued objective function with far less memory requirements (but more processing time) than DP alone.

The PATH algorithm was tested using growth look-aheads of 0 to 20 years. The results are very disappointing (table 5). Only the 5 year look-ahead performed better than DP alone. While PATH is very fast, unless the proper look-ahead length is used, it produces inferior results to straight DP.

Tables 6 and 7 show the results of adding a simple heuristic to the DP formulation. While the heuristic does not require much additional processing time, the only improvements to DP occur when state neighborhoods are very large and grossly violate the principle of optimality.

Table 4.—*Testing a 5-year look-ahead on various DBH-NT state neighborhoods and comparing to straight DP*

State neighborhoods			Results w/o look-ahead			Results w/Look-ahead		
DBH	NT	# States	SEV	Time	Stages	SEV	Time	Stages
inches			*$/acre*	*seconds*		*$/acre*	*seconds*	
0.2	1	90626	320.3	38597	26	329.6	107758	40
0.2	2	45426	320.3	19726	26	329.6	51564	40
0.2	5	18306	294.2	8633	27	329.3	20443	36
0.5	5	7371	281.4	3450	26	329.3	8069	36
0.5	10	3731	279.9	2286	36	327.2	4067	36
1.0	10	1886	278.2	830	24	322.9	1694	26
1.0	20	966	249.0	417	30	322.9	905	26
2.0	20	504	238.4	230	33	322.9	518	26

Table 5.—*Testing various growth look-aheads using the PATH algorithm*

Length of look-ahead	Objective function	Time to solve value	Stages
years	*$/acre*	*seconds*	
0	225.1	464	24
1	225.1	492	24
2	225.1	467	24
5	320.8	537	26
10	261.2	664	34
20	245.8	572	28

Table 6.—*Testing various heuristic parameters on DP state neighborhoods DBH=0.5" and NT = 5/acre*

b_1	b_2	Objective function value	Time	# of stages
		$/acre	*seconds*	
—	—	281.4	3450	26
4	0	281.4	3592	26
8	0	281.4	3551	26
16	0	288.0	4773	35
32	0	281.4	3914	26
0	-1.0	281.4	3570	26
0	-2.0	289.7	3793	27
0	-4.0	289.7	3958	27
0	-8.0	289.7	4011	27
16	-2.0	289.7	3665	27
0	4	294.2	3787	27
16	4	294.2	3733	27
20	0	278.2	3447	26

Table 7.—*Testing the best heuristic found ($b_1 = 0$, $b_2 = 4$) to various DBH-NT state neighborhoods and comparing to straight DP*

State neighborhoods			Results without look-ahead			Results with Look-ahead		
DBH	NT	# States	SEV	Time	Stages	SEV	Time	Stages
inches			*$/acre*	*seconds*		*$/acre*	*seconds*	
0.2	1	90626	320.3	38597	26	320.3	37887	26
0.2	2	45426	320.3	19726	26	320.3	21283	26
0.2	5	18306	294.2	8633	27	294.2	8666	27
0.5	5	7371	281.4	3450	26	294.2	3787	27
0.5	10	3731	279.9	2286	36	280.0	1743	25
1.0	10	1886	278.2	830	24	278.2	916	24
1.0	20	966	249.0	417	30	270.3	511	23
2.0	20	504	238.4	230	33	270.3	302	23

CONCLUSION

It is apparent that adding a growth look-ahead to the DP formulation can improve the value of the objective function without additional memory requirements but at a cost of two to three times more processing time. PATH is very fast and can provide "good" results, but obviously, the growth function is not monotonic. Thus, PATH cannot find solutions as good as DP or DP+look-ahead. The DP+heuristic is marginally effective on suboptimal DP neighborhoods, but the testing here was very rudimentary. It may be possible to devise better heuristics that will perform better than the simple ones here.

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EVALUATION OF DIFFERENT OPTIMIZATION MODELS FOR SCHEDULING SILVICULTURAL OPERATIONS

André Laroze, Paulina Pinto, Fernando Muñoz[1]

ABSTRACT.—Currently in Chile, silvicultural tasks present the highest level of labor instability among forestry activities. Due to their seasonal character and short duration, a continuous change of nonspecialized workers is generated. To help reverse this situation it is necessary to consider cost and labor stability simultaneously to determine in advance the number of workers required to perform such tasks. The objective of this study was to develop and compare several models for solving this problem, based on different objective functions and constraint sets. The results obtained indicate that the analyzed models can contribute to effective scheduling of a company's silvicultural activities at an operational level.

INTRODUCTION

The forestry sector is currently one of the most dynamic agents of the Chilean economy. In an open economy, however, the productive factors constantly change and the activities become more competitive and less profitable. This situation has led forestry companies to develop new techniques for improving the return on their investments by means of increasing yields, optimizing production systems, and minimizing operational costs.

Mathematical programming models can find good solutions for a variety of problems such as selection of management regimes, log merchandising, and transportation scheduling. However, the problems analyzed by forestry companies have mainly dealt with efficient resource allocations at a strategic (Barros and Weintraub 1982, García 1984) and tactical level (Laroze and Greber 1991, Weintraub *et al.* 1994). Simulation and optimization techniques have been used less frequently for solving operational problems; their absence in scheduling silvicultural activities is particularly notorious (Muñoz and Andalaft 1991).

Silvicultural interventions present the highest level of labor instability within the Chilean forestry sector. The seasonal character and short duration of these tasks translates into a continuous rotation of nonspecialized workers. This situation could be reversed by considering aspects of cost minimization and labor stability simultaneously when scheduling silvicultural activities; that is, keeping the work force as regular as possible and thus reducing the normal monthly fluctuations without affecting operational costs. Such a planning effort can improve the use of forest camps, increase the companies' administrative efficiency, and achieve a labor stability that should stimulate a worker-training program by the forestry contractors.

This study developed several optimization models to schedule a company's silvicultural tasks considering a 1-year planning horizon. The lack of proven models for solving this type of problem made it necessary to design and evaluate alternate formulations. The approach of implementing different objective functions and constraint sets and later comparing the results in terms of cost and labor stability allowed us to establish a process for generating cost-effective solutions at an operational level.

BASIC INFORMATION

Forestal Mininco's Department of Forest Management—Concepcion Region provided the data corresponding to the silvicultural activities. Information on 20 tree farms that represented diverse conditions was extracted from the 1995 annual plan. For each tree farm, the data consisted of the area, cost, labor productivity, and feasibility periods for eight silvicultural interventions. A 12-month planning horizon was considered. The extension of the planning horizon, number of tree farms, and number of tasks selected correspond to a real-size problem representative of the decisions carried out at a district level (the company's basic administrative unit).

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PROBLEM MODELING

Based on the annual program established for the silvicultural activities, it is possible to use mathematical programming techniques for efficiently determining the work force required for performing each task at each tree farm on a monthly basis. The input required consists of the periods in which it is feasible to perform the tasks, the expected labor productivity and cost, and the available budget.

Since the problem of scheduling silvicultural tasks was not clearly defined, we evaluated several models generated as a combination of different objective functions and constraint sets. Thus, one could analyze multiple scenarios and compare the optimal solutions obtained by the different formulations. The following section presents the different objective functions and restrictions considered.

Objective Functions

- *Minimization of total cost* finds the solution that minimizes the total cost incurred for carrying out all of the silvicultural interventions in every tree farm.
- *Minimization of total labor* generates the solution that minimizes the work force required to execute all of the silvicultural tasks.
- *Minimization of the work force variance* reduces the variance in the number of person days hired throughout the season, and therefore, is a proxy for maximizing labor stability.
- *Minimization of the maximum work force required per* lowers the highest labor requirements for any particular month. Therefore, it indirectly attempts to reduce the total number of workers required during the season, and to standardize the work load in the different periods. Restrictions that ensure a positive difference between the objective value and the number of person days hired in every period of the season complement this function.

Constraints

- *Annual program (A)* forces the solution to perform the annual program of silvicultural activities in every tree farm. It is implemented in all models.
- *Range of allowable person days per period (R)* requires that the number of person days per month that neither exceeds a maximum boundary nor is lower than a minimum target, taking into account all the tasks in the different tree farms. This range regulates the work load distribution in absolute terms.
- *Work force fluctuation (F)* keeps the relative differences in the number of person days hired in consecutive months within a predetermined percentage.
- *Minimum and maximum monthly size per activity at each tree farm (S)* force each silvicultural task to have a minimum extension, defined by a practical limit that makes its execution convenient, and not to exceed a maximum size, set by an operational monitoring limit.
- *Continuity condition (C)* encourages the tasks to be carried out without interruptions by associating a cost to each beginning and ending of a task. If the assigned costs are high enough, the continuity conditions become implicit restrictions.
- *Maximum total cost (P)* keeps the solution from exceeding the available budget for executing the total number of tasks in the different tree farms.

ANALYSIS OF RESULTS

A large number of models can be defined by combining different objective functions with diverse groups of restrictions. For this study, however, the analysis was focused on the issues that are described below.

Basic Parameters Used for Restrictions

Table 1 lists characteristics of two optimization problems considered in this study. Table 2 presents the base values of the different restrictions that were considered for the problems. A maximum variation of ±10 percent is accepted in the fluctuation of the number of person days hired in consecutive months. As for the work force allowed to be hired each month, the minimum was set at 5,850 and the maximum at 7,150 person days for all the periods. These values correspond to approximately 10 percent variation regarding the average number of hired person days per month (6,517), according to the solution of the variance minimization objective function subject to the execution of the operative plan. For each task, the minimum and maximum size of a monthly silvicultural intervention carried out in a tree farm are indicated in this table, as well as the constant for determining the condition of continuity (0.1 hectares) and the maximum total cost. This last value, which is used as a reference, corresponds to the solution of the model for minimizing total cost subject to the execution of the annual plan.

Comparison of Objective Functions

This analysis was carried out to compare the behavior of the four basic models. These models consist of each one of the objective functions and only consider the restriction

Table 1.—*Characterization of two optimization problems*

Criteria	Problem A	Problem B
Objective Function	Minimize total cost	Minimize total cost
Type of restrictions	Annual program (A)	Annual program (A) Range of allowable person days per period (R) Work force fluctuation (F) Minimum and maximum monthly size per activity at each tree farm (S) Continuity condition (C)
Number of variables	364	1,456
Number of complete variables	0	1,092
Number of restrictions	100	1,354
Number of nonlinear restrictions	0	0
Coefficients other than zero	3,213	10,195

Table 2.—*Base parameters used for restrictions*

Silvicultural activity	Area	
	Minimum	Maximum
	- - - - *hectares* - - - -	
A	15	85
B	15	100
C	20	80
D	20	100
E	10	150
F	25	225
G	25	225
H	20	250

Continuity constant [ha]: 0.1
Maximum total budget: $1,675,525

for executing the silvicultural interventions according to the company's operative targets. Furthermore, such solutions are compared with those that result from including an additional constraint that regulates the monthly minimum and maximum area of the tasks. Thus, it is possible to evaluate the effect of these restrictions—in terms of cost and labor stability—according to the type of objective function.

With regards to the analysis of the basic models, table 3 shows that the objective function of total cost minimization, which is the most efficient in economic terms, presents a great monthly variation in the budget and work force required. The objective function for minimization of total person days also generates a high operative instability, and even though it obtains a better average productivity, it induces an increase in the total cost. This situation is due to the fact that periods of better physical yield in the tasks do not necessarily coincide with lower operational costs. Upon comparing both solutions, an increase of 3.6 percent with regards to the total cost (from thousand-$ 1,676 to 1,736) and a decrease of 3.5 percent in the number of required person days (from 76,490 to 73,793), is observed.

Figure 1 presents the work force distribution per month corresponding to the solution obtained for each of the basic models. One can observe that the objective functions minimizing the maximum monthly work force (MMW) and the variance in the number of person days generate a homogeneous distribution of work all year round. However, this greater labor stability implies an important increase in costs, which affects variance minimization more. In particular, the latter objective function, which is insensitive to cost and total number of person days, achieves greater labor stability by means of an inefficient assignment of tasks. That is, in order to even out the work force in the months of less activity, it allocates the tasks of poorest productivity. Consequently, this solution implies an increase of 8.7 percent in costs and 5.4 percent in person days, compared to the solution for the objective functions of minimizing total cost and person days, respectively.

Upon analyzing the solutions at a tree farm level, it was observed that the objective functions of minimizing costs and person days concentrate the completion of each task only in the month that is most convenient. In several cases, these solutions exceed the contractors' actual work load capacity. On the other hand, the objective functions of minimizing MMW and variance generate solutions that imply levels of very low activity per month on some

tree farms that do not justify keeping a task open. To solve this inconvenience, a constraint was added that limits the minimum and maximum area that a task should have on a property in a month. Table 3 shows that this additional restriction generates an important increase of the operational costs for the objective functions of minimizing costs and person days, but it also reduces the variability of monthly activity levels. In the case of the other two objective functions, the effect of the added constraint had a lower impact on costs but decreased labor stability.

The solution time is negligible for the basic models, including that of variance minimization, which is the only nonlinear programming model. Regarding the problems with integer variables, a significant increase in the number of iterations took place for MMW model, but the solution time did not exceed 10 minutes on a Pentium Intel-166 MHz computer. However, with the variance minimization problem, a nonlinear integer model, the processing time exceeded 24 hours even when the solution corresponding to the MMW model was used as an initial starting point. Therefore, the best feasible solution obtained within a limit of 250,000 iterations was selected in this case.

Effect of the Restriction Levels

For the objective function of minimizing the total cost, models with three types of constraints were formulated: completion of tasks, range of person days, and maximum work force fluctuation. The analysis consisted of defining diverse restriction levels for the last two types of constraints, where each level corresponds to a certain value for the parameters associated with the constraint. These tests enabled us to assess the effect of the different requirements of work force distribution stated in the problem on the costs and labor productivity.

Table 4 shows that, by restricting the fluctuation in the number of person days between consecutive periods, one can achieve a considerably more even level of activity upon using the objective function of minimizing the total cost. However, the changes in the number of person days represent a trend: the difference accumulated in an interim of 6 months is close to 35 percent for a tolerated fluctuation of 10 percent (4,555; 7,336; and 5,374 person days for months 1, 6, and 12, respectively).

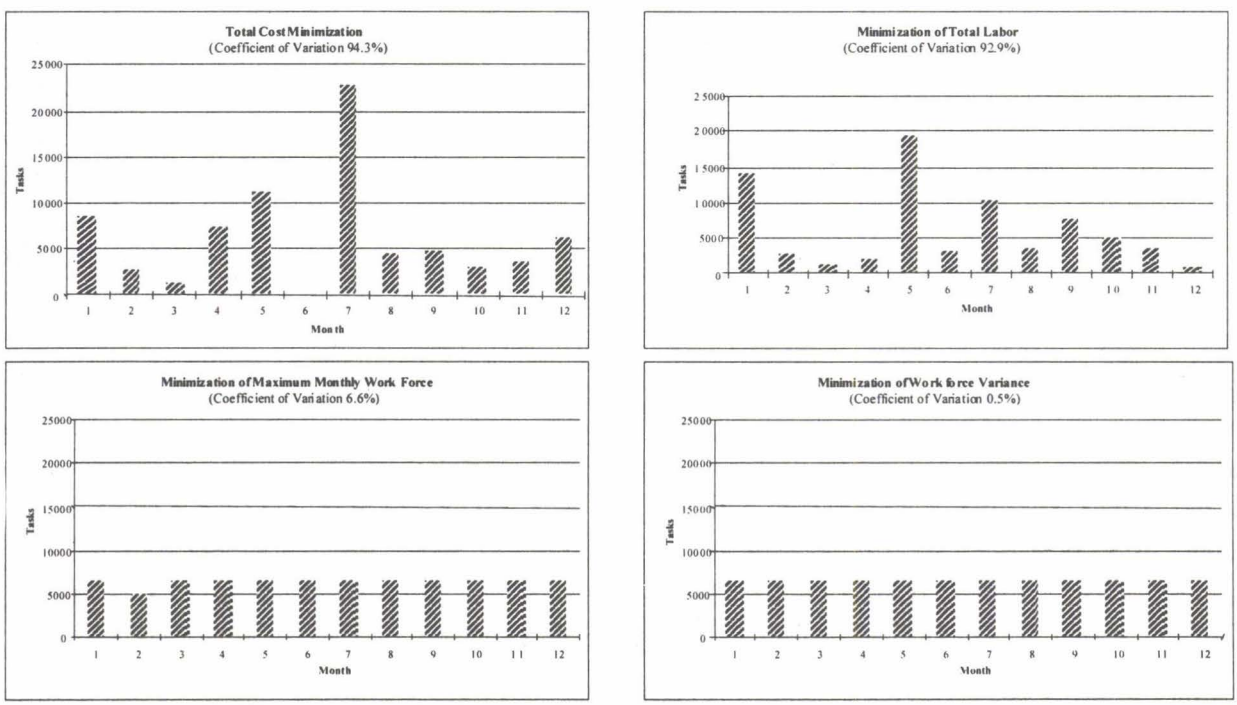

Figure 1.—*Monthly work load distribution according to selected objective function.*

Table 3.—*Comparison of objective functions*

Analyses minimize:	Subject to:	Total	Average monthly results						Solution process	
			Mean	Median	Minimum	Maximum	Range	CV	Iterations	Time
Cost			*thousand dollars*					*percent*		
Total cost	A	**1676**	140	92	0	444	444	87.2	1	00:00:01
Total labor	A	1736	145	83	17	469	453	91.6	1	00:00:01
MMW	A	1794	149	145	118	180	62	13.5	221	00:00:08
Work force variance	A	1821	152	147	121	180	58	11.9	220	00:02:02
Total cost	A, S	**1709**	142	109	91	311	220	48.7	954	00:00:32
Total labor	A, S	1759	147	133	56	303	246	49.4	991	00:00:34
MMW	A, S	1816	151	149	99	183	84	16.3	26802	00:08:14
Work force variance	A, S	1825	152	145	126	183	58	14.1	250000	24:10:53
Work force			*person days*							
Total cost	A	76490	6374	4714	0	22688	22688	94.3		
Total labor	A	**73793**	6149	3606	880	19450	18570	92.9		
MMW	A	77088	6424	6546	5077	**6546**	1469	6.6		
Work force variance	A	78208	6517	6517	6486	6551	65	**0.5**		
Total cost	A, S	78405	6534	5141	3323	16345	13023	58.4		
Total labor	A, S	**75915**	6326	6255	2703	12165	9463	48.3		
MMW	A, S	78403	6534	7078	4263	**7078**	2815	15.1		
Work force variance	A, S	78519	6543	6534	5931	7147	1216	**8.5**		
Productivity			*person days/hectare*							
Total cost	A		4.13	3.92	1.89	10.50	8.61	73.2		
Total labor	A		3.99	3.51	2.10	11.00	8.90	80.7		
MMW	A		4.16	3.88	3.07	9.15	6.08	40.4		
Work force variance	A		4.23	3.95	3.07	6.30	3.23	21.6		
Total cost	A, S		4.24	4.23	2.84	9.45	6.61	50.1		
Total labor	A, S		4.10	4.08	2.68	9.85	7.18	54.9		
MMW	A, S		4.24	4.15	3.28	8.20	4.92	33.0		
Work force variance	A, S		4.24	4.17	3.28	6.75	3.48	23.0		

A = Annual program; S = Minimum and maximum size per activity at each tree-farm; CV = variation coefficient.

Table 4.—*Effect of the restriction levels on cost, work force, and productivity when attempting to minimize total cost*

Analyses	Monthly results												General results		
Restrictions:	1	2	3	4	5	6	7	8	9	10	11	12	Total	Mean	CV
Cost	*thousand dollars*														*percent*
A	208	79	39	182	270	0	444	81	104	80	70	119	**1676**	140	87.2
A, F_1	99	112	147	159	169	200	201	141	134	139	96	109	**1707**	142	25.1
A, F_B	109	117	153	154	160	178	161	163	154	150	116	103	**1717**	143	17.4
A, F_2	120	136	162	155	157	164	152	144	158	137	135	117	**1738**	145	10.9
A, R_1	174	113	44	177	170	173	158	132	157	150	151	119	**1718**	143	26.4
A, R_2	132	141	162	149	140	140	137	244	126	129	117	111	**1728**	144	23.8
A, R_B	133	141	162	149	170	174	155	134	156	132	119	111	**1737**	145	13.6
A, F_B, R_B	133	141	162	161	168	174	161	129	149	133	118	111	**1738**	145	14.1
Work force	*person days*														
A	8710	2800	1335	7413	11095	0	22688	4590	4838	3093	3675	6255	76490	6374	94.3
A, F_1	4097	4712	5418	6231	7166	8241	9477	8055	6847	5820	4947	5689	76700	6392	25.2
A, F_B	4555	5011	5512	6063	6669	7336	8070	8191	7372	6634	5971	5374	76757	6396	18.5
A, F_2	5318	5584	5863	6157	6464	6788	7127	7483	7109	6754	6416	6095	77160	6430	10.2
A, R_1	7150	4360	1529	7150	7150	7150	7150	7150	7150	7150	7150	6255	76494	6374	27.2
A, R_2	5850	5850	5850	5850	5850	5850	6022	13233	5850	5850	5850	5850	77755	6480	32.8
A, R_B	5850	5850	5850	5850	7150	7150	7150	7150	7150	6131	5850	5850	76981	6415	10.2
A, F_B, R_B	5850	5850	5850	6435	7079	7150	7150	7150	6770	6093	5850	5850	77077	6423	9.3
Productivity	*person days/hectare*														
A	8.30	3.11	2.70	3.92	3.33	—	4.37	3.99	2.60	1.89	10.50	9.55		4.13	73.2
A, F_1	7.61	8.90	3.48	3.64	3.03	4.15	4.24	4.24	3.99	2.35	5.47	9.51		4.14	56.6
A, F_B	7.76	9.12	3.36	3.68	2.97	4.10	4.48	4.22	3.65	2.77	4.47	9.48		4.15	57.2
A, F_2	6.17	8.08	3.44	3.69	2.94	4.01	4.58	4.36	3.43	3.74	3.95	6.62		4.17	37.2
A, R_1	8.02	4.12	2.91	3.86	2.98	4.07	4.35	4.58	3.43	3.25	3.78	9.55		4.13	49.8
A, R_2	5.18	8.26	3.43	3.67	2.96	4.24	4.17	4.37	3.48	3.11	4.46	8.69		4.20	44.9
A, R_B	4.93	8.26	3.43	3.67	2.98	4.07	4.49	4.41	3.44	3.17	4.60	8.82		4.16	45.7
A, F_B, R_B	5.18	8.26	3.43	3.70	3.02	4.07	4.22	4.71	3.40	3.21	4.50	8.11		4.16	42.5

CV= Coefficient of variation; A = Annual program; F = Maximum work force fluctuation; R = Range of allowable person days per month.
(F_B = 10%, F_1 = 15%, F_2 = 5%; R_B = 5850 - 7150 person days, R_1 >= 5850 person days, R_2 <= 7150 person days.)

Defining a maximum number of person days to hire per period also improves labor distribution. However, some months of very low activity cannot be avoided, which is enough to generate rotation of labor force. Considering a minimum number of person days solves this problem but tends to concentrate a great amount of work in the most favorable month, an unrealistic solution since it is not possible to hire specialized workers for such a brief period. We obtained a better solution from the perspective of labor stability by restricting both the minimum and maximum number of person days. This situation generated only two levels of activity during the year, with each level corresponding to a boundary of the range.

The simultaneous constraints of range of person days and maximum fluctuation yield a solution that does not exceed critical limits but permits a gradual transition between the two main levels of activity that occur during the season. Also, this formulation is more effective since it produces a smaller variation of person days than any of the restrictions considered independently, without increasing the total cost.

Finally, as expected, higher demands on the conditions of the problem generate better labor stability and a more uniform productivity, but also higher operational costs.

Effect of the Type of Constraints

We defined several constraint alternatives for the objective function of minimizing total costs. In each formulation, new restrictions were added to the basic condition. The constraint that limits the work force fluctuation was included first, then the one on the range of person days was added, and so on, until the whole set of restrictions that are relevant to the problem of minimizing costs had been added.

Table 5 shows how total costs rise as the constraints of the problem increase, explaining why economic interests oppose those of labor and operative stability. For example, limiting the range of person days has a larger impact on cost than restricting the fluctuation, but it also makes the work force distribution more homogeneous. Adding the restriction of fluctuation to that of the range of person days has a minimum impact on extra costs, but shows an interesting effect on labor stability.

Simultaneously considering the constraints of minimum and maximum area per month per task and the condition of continuity avoids a series of operative problems but increases the total cost by 3.2 percent. When adding range and fluctuation considerations to such constraints, total cost increases 8.5 percent with regards to the basic model of minimizing costs (from thousand-$ 1,676 to 1,818), while the variation coefficient of the work force hired during the year decreases from 94.3 to 9.2 percent.

In terms of the computer processing time required to solve each model, the results indicate that when the complete set of constraints is used, a combinatorial problem that is difficult to solve results, due mainly to a conflict between the continuity condition and the restrictions related to work force distribution (range and fluctuation). Under this situation it was not possible to find an optimum solution in less than 2.5 million iterations, equivalent to approximately 12 hours of computer processing. However, if a tolerance of 3.5 percent were considered with regards to the theoretical limit, a good solution would have been found in nearly 30,000 iterations. All the other formulations of the problem had a solution time of less than 20 minutes.

Trade Off Analysis: Cost-Labor Stability

The problem of minimizing the work force variance was solved taking into consideration different levels for the maximum total cost allowed. Table 6 shows the main results of this analysis and figure 2 presents the curve based on these results.

This formulation of the problem defines the best labor stability one can possibly achieve without exceeding a certain budget for the execution of all the tasks. For example, a variation of 1.2 percent is obtained for a budget of $ 1.79 million. This is less than the variation of 6.6 percent for the solution of the MMW model that has the same cost (table 3). In the case of minimizing the total cost subject to range and fluctuation constraints, the variation in person days is 9.2 percent with a cost of $ 1.74 million (table 4). With the same budget, a coefficient of variation of 8.5 percent takes place when the work force variance is minimized. The variation increases to 11.4 percent as the maximum total cost allowed is lowered to $ 1.73 million.

The curve that results from the different budget levels corresponds to the most efficient transaction points in terms of the increase in cost required to obtain a better labor stability, based on a given situation. In the case analyzed in this study, the curve shows a relatively favorable cost-stability transaction with regards to labor, up to a cost of $ 1.73 million. From that point on, better stability is only achieved with considerable increases in the total cost.

Dominant Solutions

We analyzed two types of problems for the objective functions for minimizing variance and MMW. The first one only considered the execution of the program of silvicultural tasks. The second adds restrictions for the minimum and maximum area of a task per month and tree farm. Both problems included an additional constraint that limited the total cost allowed for the solution,

Table 5.—*Effect of type of constraints*

Analyses	Monthly results												Summary		Iterations
restrictions:	1	2	3	4	5	6	7	8	9	10	11	12	Total	CV	
Cost	*thousand dollars*													*percent*	
A	208	79	39	182	270	0	444	81	104	80	70	119	**1676**	87.2	1
A, F	109	117	153	154	160	178	161	163	154	150	116	103	**1717**	17.4	259
A, R	133	141	162	149	170	174	155	134	156	132	119	111	**1737**	13.6	194
A, F, R	133	141	162	161	168	174	161	129	149	133	118	111	**1738**	14.1	212
A, S	124	91	94	125	205	108	231	311	93	108	108	109	**1709**	48.7	954
A, S, C	83	112	98	91	196	96	307	294	75	125	141	112	**1729**	55.3	20316
A, S, F	104	125	148	157	165	167	172	165	165	148	125	110	**1753**	16.3	54162
A, S, R	133	141	155	182	172	176	149	137	165	126	123	120	**1780**	14.6	13844
A, S, F, R	134	142	157	172	175	190	142	139	171	134	122	127	**1806**	14.6	16265
A, S, C, F, R	135	132	163	175	175	185	141	139	176	140	120	138	**1818**	14.4	2500000
Work force	*person days*														
A	8710	2800	1335	7413	11095	0	22688	4590	4838	3093	3675	6255	76490	94.3	
A, F	4555	5011	5512	6063	6669	7336	8070	8191	7372	6634	5971	5374	76757	18.5	
A, R	5850	5850	5850	5850	7150	7150	7150	7150	7150	6131	5850	5850	76981	10.2	
A, F, R	5850	5850	5850	6435	7079	7150	7150	7150	6770	6093	5850	5850	77077	9.3	
A, S	5160	3688	3323	4640	8560	5123	11430	16345	4363	4895	5400	5480	78405	58.4	
A, S, C	3333	4290	3753	3313	7993	4430	14630	15550	3643	5345	6895	5590	78763	64.6	
A, S, F	4602	5062	5569	6125	6738	7412	8153	8429	7586	6827	6145	5530	78177	18.7	
A, S, R	5850	5850	5850	7150	7150	7150	7150	7150	7150	5999	5850	5850		10.2	
A, S, F, R	5850	5850	6077	6685	7150	7150	7150	7150	7150	6435	5850	5850		9.2	
A, S, C, F, R	5850	5850	6149	6764	7150	7150	7150	7150	7150	6435	5850	5850		9.2	

CV= Coefficient of variation; A = Annual program; F = Maximum workforce fluctuation; R = Range of allowable person days per month; S = Minimum and maximum size per activity at each tree-farm; C = Continuity condition.

Table 6.—*Trade-off analysis when trying to minimize work force variance: cost-labor stability*

Analyses subject to:	Total	Monthly results				Range	CV
		Mean	Median	Minimum	Maximum		
Cost		*thousand dollars*					*percent*
A	1821	152	147	121	180	58	11.9
A, P_1	1790	149	147	123	180	58	12.7
A, P_2	1760	147	145	115	178	62	12.8
A, P_3	1730	144	142	113	176	63	12.8
A, P_4	1700	142	132	103	193	90	22.6
A, P_B	1676	140	111	63	272	209	50.7
Work force		*person days*					
A	78208	6517	6517	6486	6551	65	**0.5**
A, P_1	77861	6488	6482	6411	6579	168	**1.2**
A, P_2	77003	6417	6396	6190	6657	467	**3.1**
A, P_3	76917	6410	6317	5360	7427	2067	**11.4**
A, P_4	76586	6382	6324	4135	8509	4374	**24.8**
A, P_B	76875	6406	4355	2333	13604	11271	**59.7**

CV= Coefficient of Variation; A = Annual program; P = Maximum budget. (P_B = 1676 thousand-$, P_1 = 1790 thousand-$, P_2 = 1760 thousand-$, P_3 =1730 thousand-$, P_4 = 1700 thousand-$)

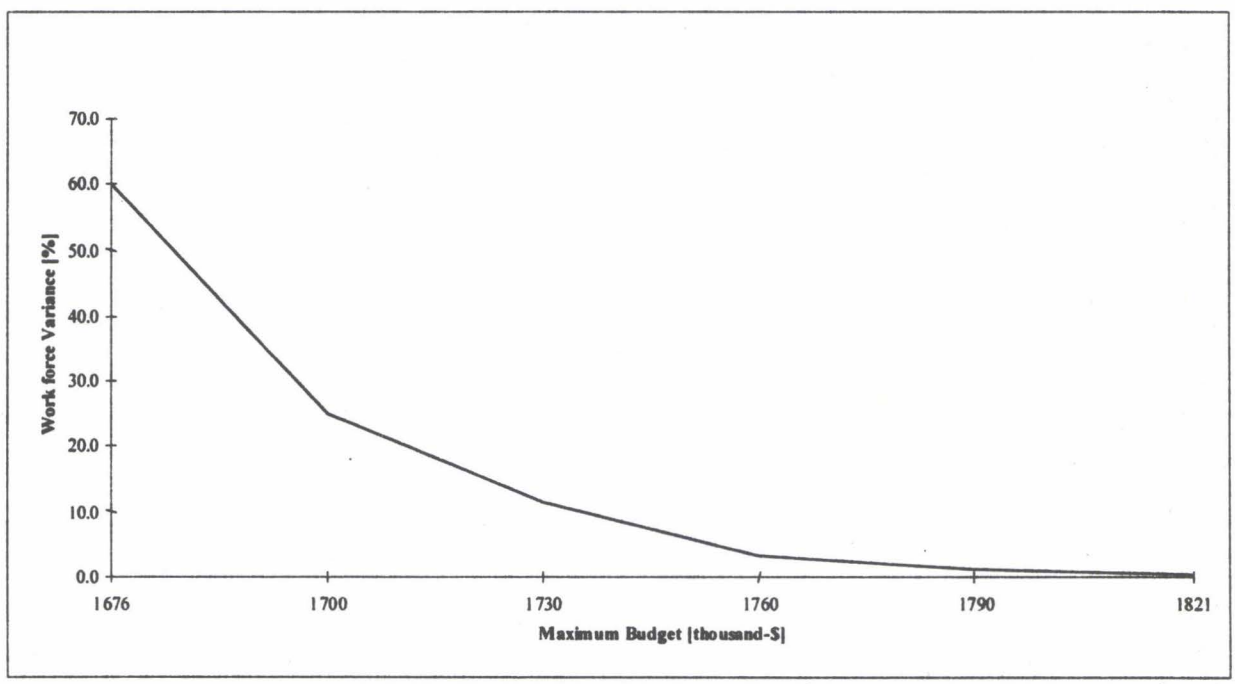

Figure 2.—*Trade-off curve: cost-labor stability.*

using the value obtained upon minimizing the cost subject to the same type of restrictions as a reference budget.

Table 7 indicates that it is possible to improve labor stability without increasing operative costs. In models without restrictions for minimum and maximum area, the variation coefficient decreases from 94.3 to 67.0 percent, for the objective function minimizing the MMW, and to 59.7 percent, for that of minimizing the variance. For the models that include area restrictions, profits—in terms of labor stability—are less since these restrictions themselves have a regulating effect when the total cost is minimized. However, since the operative budget is larger, there is more latitude for the objective functions of minimizing variance and MMW to find a more stable labor solution, with a drop in the variation coefficients from 59.7 to 48.5 percent, and from 67.0 to 53.5 percent, respectively.

Given the same budget limit, the best answer, in terms of labor stability, is achieved with the minimum variance model. However, it should be kept in mind that this objective function is a quadratic form, which becomes a difficult problem to solve with integer variables. The objective function of minimizing MMW, on the other hand, is a min-max type model of linear nature, that enables obtaining solutions in considerably less time, more so when the size of the problem increases.

The optimization procedure employed generates dominant solutions in the sense that they tend to maximize labor stability without increasing the total cost. By solving the problem of minimizing total costs, the most economically convenient solution is obtained. When employing the resulting value as a budget restriction in models oriented to level out the work force distribution, it is possible to achieve the best final solution from the perspective of combining two conflicting interests.

CONCLUSIONS

The models mentioned in the different analyses that have been carried out highlight how the problem of scheduling silvicultural tasks can be formulated in multiple ways according to the objectives and priorities considered at the moment of planning the activities.

The objective function of minimizing total costs prioritizes economic interests. Nevertheless, it is possible to significantly improve labor stability by restricting the range of person days to be hired and their maximum fluctuation over time. The best results are achieved combining both restrictions, since the second one only controls the variation between consecutive months, but does not avoid the fluctuations accumulated throughout the season. This situation is corrected by restricting, in absolute terms, the minimum and maximum work force to be hired in any period.

The best work force distribution in the season is obtained through the objective function that minimizes the person days variance, although the model employs a poor allocation of productivity that conveys higher operational costs in order to achieve this distribution. The objective function of minimizing MMW tends to standardize the distribution of person days as well. It has the advantage of being a linear model that requires a shorter solution time. Also, it tends to generate less demand of labor force and, consequently, a lower total cost. However, this objective function becomes indifferent to the distribution of person days through time once it is not possible to reduce the work force required for a certain month. Therefore, it is not very effective when activity levels vary much during the year.

The results of this study show how economic interests oppose those of labor and operative stability. Consequently, it is necessary to compare several formulations in order to achieve a solution that harmonizes the different interests of the company. In particular, the generation of dominant solutions presents a good option for overcoming conflicting objectives by allowing an improvement in labor stability without increasing total costs.

In general, through the type of analysis carried out in this study, one can determine the effect that the objective function and the different constraints have in the solution of the problem. Also, it enables the professional entrusted with the planning of silvicultural tasks to evaluate the additional costs that are implied to satisfy the diverse requirements of the company. This study highlights the importance of applying mathematical programming techniques for efficiently planning silvicultural tasks at an operative level.

ACKNOWLEDGMENTS

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Table 7.—*Generation of dominant solutions*

Analyses		Total	Average monthly results					
Minimized item	**Subject to**		**Mean**	**Median**	**Minimum**	**Maximum**	**Range**	**CV**
Cost			*thousand dollars*					*percent*
Total cost	A	**1676**	140	92	0	444	444	87.2
MMW	A, P_B	1676	140	124	39	278	239	60.9
Work force variance	A, P_B	1676	140	111	63	272	209	50.7
Total cost	A, S	1709	142	109	91	311	220	48.7
MMW	A, S, P_S	1709	142	117	62	255	193	46.5
Work force variance	A, S, P_S	1709	142	114	94	258	164	40.1
Work force			*person days*					
Total cost	A	76490	6374	4714	0	22688	22688	94.3
MMW	A, P_B	76903	6409	6228	1335	**13604**	12269	67.0
Work force variance	A, P_B	76875	6406	4355	2333	13604	11271	**59.7**
Total cost	A, S	78405	6534	5141	3323	16345	13023	58.4
MMW	A, S, P_S	77863	6489	5385	2148	**12869**	10721	53.5
Work force variance	A, S, P_S	78287	6524	5121	3323	12863	9540	**48.5**

CV= Coefficient of variation; A = Annual program; S = Minimum and maximum size per activity at each tree-farm; P = Maximum budget. (P_B = 1676 thousand-$, P_S = 1709 thousand-$.)

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A STAND OPTIMIZATION MODEL DEVELOPED FROM DYNAMICAL MODELS FOR DETERMINING THINNING STRATEGIES

Oliver Chikumbo, Iven M.Y. Mareels, and Brian J. Turner[1]

ABSTRACT.—The "curse of dimensionality" common in dynamic programming (DP) formulations of the thinning strategy problem has previously been overcome by applying the neighborhood storage location concept. However, several forest analysts are aware that the solutions obtained in this manner are suboptimal. Even worse, there is no easy way of determining how far a particular solution may be removed from optimality. Here we present an approach using dynamical models. The application of control theory can then be used to effectively overcome the dimensionality problem. Moreover, we may exploit optimization routines capable of guaranteeing optimality. In this paper, we describe how this approach has been used to address the thinning problem for *Pinus radiata* D. Don plantations in the Australian Capital Territory.

INTRODUCTION

The management of a plantation forest includes, among other things, defining operational area units and estimating the growth and yield for each unit under a set of alternative activities (harvesting/silvicultural strategies). Each land unit may have different levels of site productivity, making it difficult to determine an optimal harvesting strategy at a stand level. Forest analysts have used multistage optimization to determine the harvesting strategies that best satisfy specific objectives. Because of the daunting mathematical extent of optimization formulations, "simulators" have been used to determine silvicultural strategies, but these cannot indicate whether the outcomes are optimal or suboptimal. Simulators are computer-based, decision-support systems that enable experimentation on a model rather than on the forest itself to evaluate the forest behavior under different conditions (Ljung 1987). Multistage optimizers enable control or guidance, generally defined as the directed influence, on a dynamic system to achieve a desired outcome (Luenberger 1979).

Dynamic programming (DP) is a technique commonly used by forest analysts to solve multistage optimization problems for harvesting stands. However, the technique has not been implemented without presenting its own difficulties that Bellman (1957) called the "curse of dimensionality." The curse of dimensionality results from the need to define all the possible states at each stage of a DP formulation that can be computer-memory demanding, even for small DP problems. To counter the dimensionality problem, forest analysts have developed a DP formulation that requires the user to specify possible states that are common to all the finite stages in the planning period (Buongiorno and Gilless 1987). For brevity, this formulation will be referred to as the "forestry-DP." The forestry-DP formulation requires specification of a finite number of states (usually two to three states at each stage). The choice of these states is based on expert knowledge of the forests in question. The stages are normally specified at equal intervals of 5 to 10 years. This neighborhood storage technique is very limiting in that decisions are confined to long interval points and there is no exhaustive search of the states at each stage. Therefore, there is no guarantee of finding a global optimum over the planning period and there is no easy way of checking whether the solution is suboptimal or optimal. The forestry-DP formulation can be described as a heuristic method combined with recursive optimization. In contrast, DP employs the embedding technique that enables an exhaustive search of all the possible states at each stage in a backward recurrence mode.

Arthaud and Klemperer (1988) concluded that neighborhood storage combined with a forward recursion optimization resulted in violation of the principle of optimality;

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this formulation led to loss of paths that would have been optimal over the long run, but were discarded because of lower values (generated through thinning). Some authors (e.g., Anderson and Bare 1994, Arthaud and Klemperer 1988, Arthaud and Warnell 1994, Pelkki 1994, Valsta 1994) have deduced that they may be just achieving local optima.

Chen *et al.* (1980) concluded that some of the problems of the forestry-DP formulation were caused by the use of inappropriate growth models that did not relate directly to the decision variable and the lack of a clear definition of the conditions that had to be met for optimality.

In this paper, basal area models are developed for *Pinus radiata* D. Don plantations in the Australian Capital Territory (ACT) from time-series data describing basal area and stand density. These models are discrete-time "dynamical models." Dynamical models are common in the field of systems engineering and describe dynamic systems where control and controlled variables are identified. For a first-order, discrete-time dynamical model, the current observation at time *t* depends on the previous observation at time *t-1*. For a second-order model, the observation at time *t* is dependent on the previous observations at times *t-1* and *t-2*. Time is implicit in a discrete-time dynamical model and is used as an integer to indicate equidistant observations (Chikumbo 1997). Dynamical models may be represented using input/output (thinning/basal area) variables only or using input/state/output (thinning/basal area, stand density/basal area) variables. The input/state/output representation enables one to steer a dynamic system from an initial state to a final state via the control action. A multistage optimization problem for determining optimal thinning strategies was formulated based on a state space model and solved using the maximum principle (MP), a technique similar to DP (Pontryagin 1959).

Data

The softwood plantation resource in the ACT (149° E, 35°19 min) has a net productive area of 14,500 hectares (ha) with *P. radiata* as the main species. The plantations were established on degraded pastures and land cleared of eucalypt forest. The annual rainfall in the ACT ranges from 610 to 1,140 millimeters (mm). The soils are generally poor and are derived from acid volcanics, granodiorites, and sediments. The plantation area comprises Kowen, Pierce's Creek, Stromlo, and Uriarra forests. A summary of rainfall and geology of the four forest areas is given in table 1.

A 5-year soil survey program is currently being undertaken by ACT Forests Branch on a 150 by 150-meter (m) grid. This will provide useful information for site-specific silvicultural management.

The data used for model development were collected from a number of permanent yield plots established in the 1940's through the 1970's by the then ACT Forests Branch, Australian Forestry School, and Commonwealth Forest Research Institute. The plots ranged in size from 0.01 to 0.1 ha and usually had a rectangular shape. The stocking densities at establishment ranged from 750 to 2,990 stems ha^{-1}. Thinnings were mainly frequent and light, making it difficult to estimate their effects on growth volume production. In total, the data were from 240 plots that had been measured on 3,637 occasions. Table 2 summarizes the data from the four forest areas in the ACT.

MODEL DEVELOPMENT

There was no consistency in timing and intensity of thinning from the permanent growth plots. Therefore, to develop a basal area model responsive to thinning at different intensities and timing, we selected prolonged periods of basal area measurements between any two successive thinnings from the permanent plots. Interpolation was carried out for any two successive data points that were more than 1 year apart so as to have annual records. We did this for each of the forest areas. Basal area models were identified, using subsets of the series of basal area measurements from various plots for each of the forest areas. Kowen, Pierce's Creek, Stromlo, and

Table 1.—*Rainfall and geological characteristics of the forests in the Australian Capital Territory*

Forest area	Rainfall	Geological Characteristics	
		Age	Description
	mm		
Kowen	± 650	Ordovician	mostly slates
Stromlo	± 700	Upper Silurian	variable, mainly acid volcanics and porphyry
Pierce's Creek	± 800	Silurian to Devonian	mostly granite to granodiorite
Uriarra East	± 800	Upper/Middle Silurian	Uriarra volcanics/Paddy River volcanics
Uriarra West	± 850	Ordovician	sedimentary slates

Table 2.—*Minimum, mean, and maximum values of stand variables of the four ACT forest areas*

Forest area	Number of plots	Age			Site index			Basal area			Stand density		
		min	mean	max	min	mean	max	min	mean	max	min	mean	max
		- - - - years - - - -			- - - - - m - - - - -			- - - m^2 ha^{-1} - - -			- - - stems ha^{-1} - - -		
Kowen	72	4	22.8	44	16.1	20.9	25.6	1.7	31.4	79.9	151	713	2,903
Pierce's Creek	50	5	22.8	57	18.7	22.5	27.2	1.1	30.9	58.6	51	679	5,182
Stromlo	3	9	23.1	39	19.1	20.2	22.2	9.4	27.6	38.4	173	588	971
Uriarra	115	4	20.9	51	16.5	24.9	31.7	0.5	31.5	99.9	9	774	2,976

Uriarra had 10, 19, 5, and 21 basal area models, respectively. The identification process of the basal area model consisted of a two-step approach:

1. For each subset of the series of basal area measurements, we identified a first order, discrete-time dynamical model that explained the general basal area growth trend.
2. We regressed the parameters of the models in 1 against initial stand density and site index for each forest area. The subsets of basal area measurements combined for each forest area had a small range of site indices, which resulted in site index not being used in the analysis. Therefore, we modeled these parameters using polynomials that were functions of stand density for each forest area.

The model was as follows:

(1) $BA(t) = aBA(t\text{-}1) + b$

where

t = time (years);
x = initial stand density (stems ha^{-1});
BA = stand basal area (m^2ha^{-1});

(2) $a = f(x)$;

(3) $b = f(x)$.

Table 3 gives the polynomials for parameters a and b for the four forest areas.

A simulation of the basal area models for three initial stand densities of 500, 1,000, and 1,500 stems ha^{-1} showed that a high initial stocking achieved a basal area asymptotic limit (as dictated by site quality) sooner than a lower initial stocking (see fig. 1). Stromlo forest showed similar trends but could not be simulated using the same initial stocking as the rest of the other forests. This was because the Stromlo model was based on only five models with 971 stems ha^{-1} as the highest stocking density. Therefore, the Stromlo model could not be reliably extrapolated beyond 1,000 stems ha^{-1}. A low stocking showed a slower rate in taking advantage of the available site compared with the high stocking. For all the forest areas, the basal area gain was not substantial for a higher stocking. The comparison between high stocking and low stocking for the ACT forests suggests that thinning has to be minimal otherwise the residual trees may not have the ability to fully occupy the site (maximizing basal area per tree). Rotations also have to be as long as possible for value production regimes such that the final crop can reach the largest size that a site can allow.

Table 3.—*Forest areas, their polynomial functions for a and b, and R-squared values*

Forest area	Polynomial functions	R-squared values
Kowen	$a=-0.0000000486x^2+0.0000813x+0.868$	0.80
	$b=0.00000132x^2-0.00207x+5.085$	0.78
Pierce's Creek	$a=-0.0002x+1.0339$	0.82
	$b=0.0102x-0.5463$	0.92
Stromlo	$a=-0.0000000956x^2+0.0002x+0.814$	0.68
	$b=0.0000123x^2-0.01718x+9.908$	0.81
Uriarra	$a=-0.000037x+0.9941$	0.77
	$b=0.002x+1.7606$	0.89

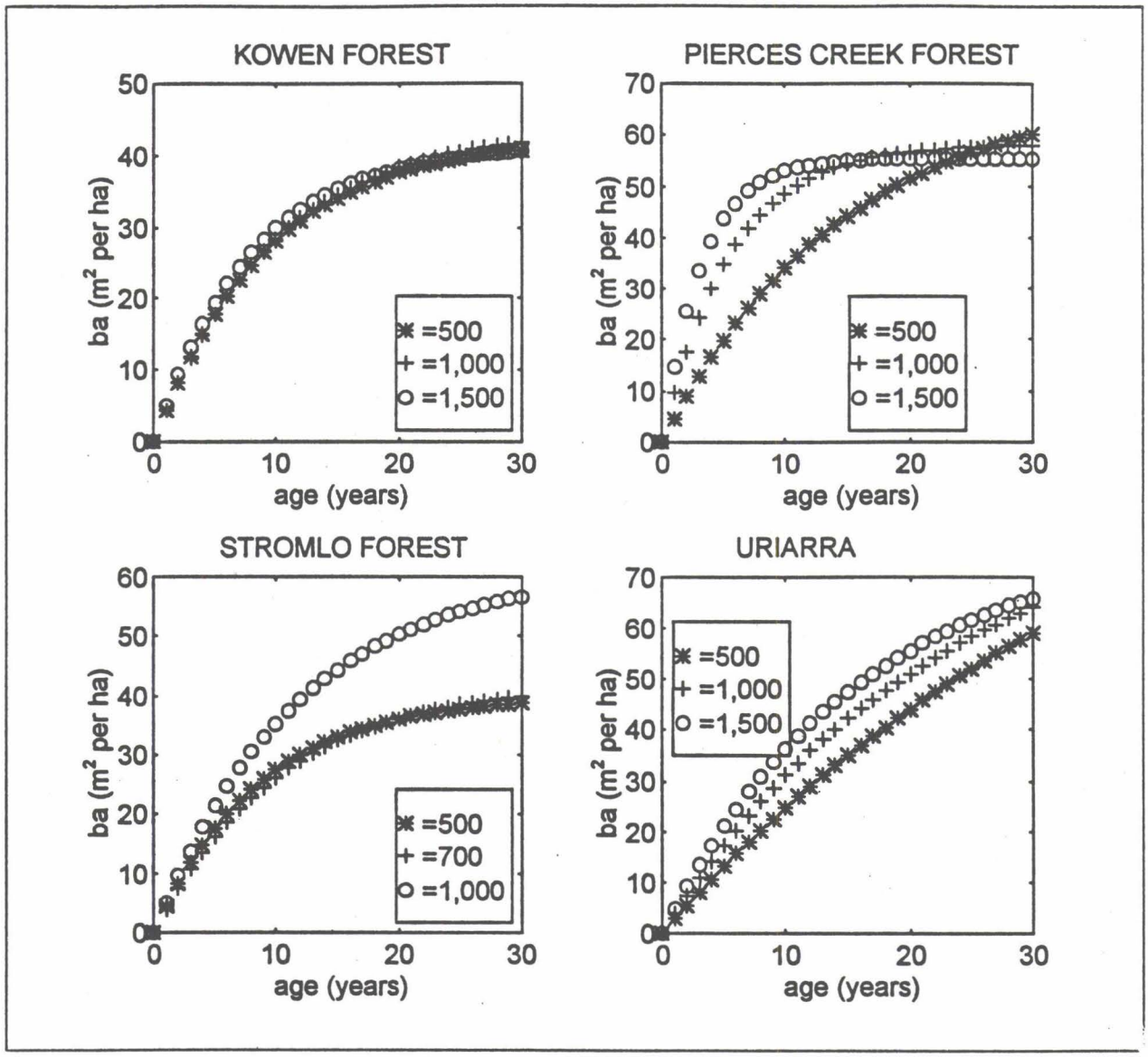

Figure 1.—*Simulation of basal models for three initial stand densities on each of the ACT forest areas.*

Kowen forest showed very little variation in basal area growth from the three simulations. The area has poor, shallow soils and low rainfall. The ACT Forests Branch has confirmed that they aim to maintain basal area at 20 m^2 ha^{-1} because of low productivity in this forest area. Pierce's Creek and Uriarra forests showed comparatively higher basal areas at age 30 because of the relatively better soils and rainfall.

Optimal Control

We considered the following optimal thinning problems:

$$(4)\ \underset{u,z}{\text{minimize}}\left\{Jvol(u,z) = -\sum_{t=0}^{n}\frac{u(t)}{x(t)} * BA(t)\right\}$$

for volume production and,

$$(5)\ \underset{u,z}{\text{minimize}}\left\{Jval(u,z) = -\sum_{t=0}^{n}\frac{u(t)}{x(t)} * \frac{BA(t)}{x(t)} * BA(t)\right\}$$

for value production. The cost functional *Jvol* is a measure of the total basal area harvested. The initial stocking is expressed as *z*, which has to be optimized. These minimizations are subject to the following constraints, the system equations (dynamics),

$$(6)\ x(t+1) = x(t) - u(t)$$

$$(7)\ BA(t+1) = a(x(t))BA(t) + b(x(t))$$

where $a(x)$ and $b(x)$ are defined in table 2. The above system equations have to be completed with the initial conditions,

(8) $x(0) = z > 0,\ BA(0) = 0,$

terminal constraint,

(9) $x(n) = u(n),$

and upper and lower bounds on thinning:

(10) $0 \le u(t) \le x(t), \forall t = 0,...,n-1$

For the above formulation $n=25$, but this also could have been left as a free variable to be optimized.

Notice that $u(t)/x(t)$ indicates the fraction of trees harvested at time t. The cost functional *Jval* puts more emphasis on bigger trees, due to the presence of the weighting factor $BA(t)/x(t)$ which is the average basal area per tree. Given more information on costs of establishment, thinning, pruning and so on, an economic component can be incorporated in the cost functional to be optimized as well as in the constraints that have to be satisfied.

A software package called MISER (Jennings *et al.* 1990) was used to solve the thinning optimization problem. The algorithm in MISER uses the maximum principle technique for solving optimal control problems. The maximum principle employs the Kuhn-Tucker method (Dixon 1972) for minimizing a function subject to equality and inequality constraints. This optimization problem can be viewed as the minimization of a functional *Jvol* or *Jval* of $n+2$ variables, i.e., and $u(0),..., u(n)$ and z, subject to a set of equality and inequality constraints as described in equations 6 through 10. For all of these constraints, the appropriate Lagrangian multipliers can be determined and then optimized as an augmented cost functional. This can be solved efficiently using a gradient-based search algorithm, such as in MISER.

It is important that the functions used in formulating the optimization problem be sufficiently smooth with respect to the control variables to allow for the differentiation. This is the case with the thinning problem where all functions are at least twice differentiable with respect to the control variable. By formulating the problem in this manner, one can solve the necessary local optimality conditions for a candidate optimal thinning strategy that can be refined to satisfy all constraints. This can be achieved without the need for a global search, thus alleviating the dimensionality curse. A solution found this way (by MISER) will be a local minimum of the optimization problem at hand. Sometimes there is no guarantee that the locally optimum solution is the global minimum. This is not an issue with problem formulation 6 through 10 because there is no other minimum for such a relatively simple formulation (only two state variables).

RESULTS

Kowen and Stromlo forests had similar MISER outputs. Both value and volume production regimes had an initial stocking of 677 stems ha^{-1} with a final crop of 122 and 140 stems ha^{-1}, respectively. Thinning was light and annual. We optimized the value production formulation again with a terminal constraint set at ages 30 and 35. In both cases, the crop was maintained at 122 stems ha^{-1}. This suggested that the final crop has to be retained for as long as possible for the residual trees to take complete advantage of the available site. The interpretation of the MISER output was that an initial stocking of 600 to 700 stems ha^{-1} be adopted and light thinnings carried out at stages best determined by including financial costs in the optimization formulation. The final crop may be harvested at any time from age 25 for volume production and retained for longer periods for value production (i.e., rotation lengths of 35 years or more). ACT Forests Branch is moving towards lower stocking regimes and establishments of 650 stems ha^{-1} in Kowen forest.

Pierce's Creek and Uriarra forest areas had similar thinning regimes. There were minimal benefits in thinning for both value and volume production regimes such that exercise became one of optimizing for the initial number of trees as for Kowen and Stromlo forests. The output from MISER for a volume production regime was one with an initial stocking of 880 stems ha^{-1} and an annual thinning of 37 stems ha^{-1} until there was no crop at age 25. This result was interpreted as an initial stocking of the order of 800 to 900 stems ha^{-1} with light thinnings again best determined by financial formulation of the thinning problem. For the value production regime, the MISER output had an initial stocking of 677 stems ha^{-1} with an annual thinning of 22 stems ha^{-1} and a final crop of 122 stems ha^{-1} at age 25 that should be maintained as long as possible. The interpretation was that value production had an initial stocking of 600-700 stems ha^{-1} with light thinnings, as suggested for Kowen and Stromlo. ACT Forests Branch agreed with these conclusions because the Pierce's Creek and Uriarra forest areas have comparatively better soils and rainfall than Kowen and Stromlo forests. In fact, fertilization is an option for ACT Forests Branch. At this stage there is no pulpwood market, and therefore it is important to estimate the initial planting density.

The thinning strategy model has a huge potential as a management tool in addressing silvicultural questions that would normally require experimental plots to be established and analyzed over a number of years. Financial parameters incorporated in the model would make the assessment more realistic.

CONCLUSIONS

The thinning problem has been solved using dynamical models and formulating a multistage optimization problem. The curse of dimensionality problem has not been encountered as a result of using the maximum principle, despite treating each year as a decision stage. The interpretations of the MISER output suggested similarities with the current recommendations of silvicultural strategies to be adopted by the ACT Forests Branch, which have been derived from years of experience by field foresters.

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OPTIMIZING THE LOCATION OF HARVESTING EQUIPMENT AND ACCESS ROADS

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ABSTRACT.—Determining how to harvest and transport timber across a forested area to an outlet or existing road is a difficult problem. This paper considers the situation where an undulating landscape is represented as a series of grid cells, each relatively small with a surface defined by elevation, slope, aspect and timber quantity. Developing a operational harvest management plan involves determining a layout of access roads which connect sited tower (and skidder) units. The objective of the problem is to minimize the costs of unit placement, road building, and timber transport. A mathematical programming formulation for this problem is presented.

INTRODUCTION

The management of lands for timber provision is a difficult and time consuming process. The focus of this paper is on operational planning considerations which must determine tower (and skidder) unit placement and road access to these sites on an undulating landscape. This surface may be represented by a series of grid cells at a suitable level of resolution using a raster based geographical information system (GIS). Thus, information on slope, elevation, aspect, and timber inventory for a planning area is assumed to be available. The problem is to minimize the costs associated with the placement of units and road building. This ensures that timber transport and provision costs remain as low as possible.

Figure 1 gives a visual representation of this operational forest harvesting problem. Cells 4, 13, 19, and 32 are potential tower unit placement sites. The objective is to determine from this set of cells a specified number of units to site as well as the best road network which links the selected units to the exit site. Figure 1 demonstrates this for the selection of units at cells 4, 13, and 19 which are connected by road linkages to the exit site at cell 40. This basic problem is a critical component of the planning problem faced by the Chilean forest industry (Murray *et al.* 1997).

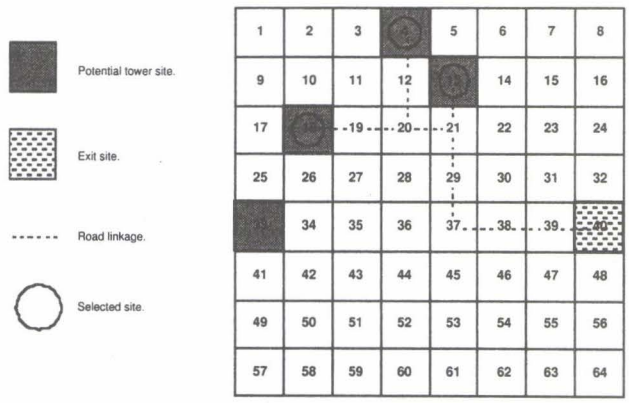

Figure 1.—*Operational forest planning problem on a grid.*

RELATED PROBLEMS

The forest management planning process is a complex task and typically involves numerous hierarchy levels of decision making (Church *et al.* 1994). Operational planning is one level in this hierarchy. The operational problem described here differs to the discrete optimization approach presented in Kirby *et al.* (1986) and Murray and Church (1995). Thus, it is a new variety of problem which stems from the data access provided by GIS and a move towards less preprocessing and preparation in the analysis of management planning.

The new operational problem discussed in this paper happens to be related to Steiner minimal tree problem. The Steiner tree problem connects a specified subset of nodes using the arcs in the network (Hakimi 1971) and has proven to be a very difficult combinatorial optimization problem. If we represent the forest planning problem described here in terms of nodes (the grid cells) and arcs (potential road links), then once we have determined

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which units to site, the problem is in fact a Steiner tree problem in a network. Thus, our problem is an extension of this difficult optimization problem.

FORMULATION

In formulating the grid based operational forest planning problem it is necessary to provide some information on how this problem is being structured. As done in Murray *et al.* (1997), the representation of this problem may be structured as a graph with nodes and arcs. The nodes are associated with the grid cells and the arcs are associated with the potential road links. The potential unit sites and exit cell also have arcs associated with them. Finally, the road link arcs are duplicated in order to track the fixed charge costs of establishing a link. We now provide the formulation of this proble.

Consider the following notation:

i,j = index of grid cells,
c_{ij} = cost to construct the road linking cell i to cell j,
t = source node related to flow through the network,
e = sink node related to flow through the network,
T = set of potential tower locations,
E = set of potential exit locations,
p^t = number of tower sites to locate.

Decision variables:

$$f_{ij} = \begin{cases} 1 \text{ if tower location } j \text{ is selected} \\ 0 \text{ otherwise.} \end{cases}$$

$$f_{ij} = \begin{cases} 1 \text{ if a road from cell } i \text{ to cell } j \text{ is built} \\ 0 \text{ otherwise} \end{cases}$$

$\bar{f}_{ij}$ = additional flow from cell i to cell j.

It is worth pointing out that the use of the additional (or duplicate) link from cell i to cell j using decision variables $\bar{f}_{ij}$ is above and beyond the use of the actual road link using the decision variable f_{ij}. Thus, f_{ij} is required to equal 1 before $\bar{f}_{ij}$ is allowed to be used.

The problem formulation is as follows:

(1) Minimize $Z_p = \sum_i \sum_j c_{ij} f_{ij}$

Subject to

(2) $\sum_i [(f_{ij} + \bar{f}_{ij}) - (f_{ji} + \bar{f}_{ji})] = 0 \ (\forall j \neq t \text{ or } e)$

(3) $\sum_{j \in T} f_{tj} = p^t$

(4) $\sum_{j \in T} f_{je} = p^e$

(5) $\sum_j f_{ij} \leq 1 \ (\forall i \neq e)$

(6) $\bar{f}_{ij} \leq (p^t - 1) f_{ij} \ (\forall i,j)$

(7) $f_{ij} = 0,1 \ (\forall i,j)$

(8) $0 \leq \bar{f}_{ij} \leq p^t - 1 \ (\forall i,j \ \& \ i \neq t)$

The objective (1) is to minimize total costs associated with siting units and building necessary roads. Constraint (2) enforces conservation of flow through the network. Constraint (3) specifies the number of tower units to site. Constraint (4) ensures that the road network is connected to the exit site. Constraint (5) requires that there be no load splitting. Constraint (6) prevents additional road link capacity unless it has been established. Constraints (7) and (8) impose integer restrictions and bounds on decision variables. Extensions to this basic formulation may be found in Murray *et al.* (1997).

DISCUSSION

Solving this problem is a difficult task, either heuristically or optimally. Murray *et al.* (1997) developed a Lagrangian relaxation heuristic approach for solving this problem. Unfortunately, only relatively small problem instances have been approached to date. Thus, solution development for this problem is a much needed area of research.

This paper has demonstrated a new variety of operational forest planning problems. A mathematical programming formulation has been presented. This problem is likely to be an important problem in the coming years as better quality spatial information becomes available through geographical information systems (GIS).

ACKNOWLEDGMENTS

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CALCULATION AND USE OF EFFECTIVE EXTERNAL BOUNDARY AND RELATED SETTING PARAMETERS IN CABLE YARDING PRODUCTION ESTIMATION

Francis E. Greulich[1]

ABSTRACT.—The concept of the effective external boundary has modified traditional methodologies used in the economic evaluation of cable settings. Environmental and safety concerns are strongly influencing silvicultural prescriptions and setting layout in the Pacific Northwest. The ability of the forest engineer to accurately evaluate economic consequences of nontraditional harvesting prescriptions and setting layouts is greatly enhanced when appropriate attention is given to design parameters such as effective external boundary and average external yarding distance. These parameters and others are easily obtained and used within the context of computerassisted layout design. Two examples based on the literature illustrate the application.

INTRODUCTION

In the nottoodistant past, cable settings in the Pacific Northwest (PNW) were laid out by forest engineers within a welldefined slowly changing operational environment. Despite occasional difficulties with specific settings, logging operators generally felt very comfortable in the conduct of their operations. Indeed it was often said that anyone could make money logging oldgrowth timber. Clearly times and conditions have changed.

Secondgrowth timber, very competitive bidding for logging contracts, high regional labor costs, shorter contract execution times, silvicultural practices that emphasize high quality residual stands, stronger environmental safeguards and stricter enforcement of safety regulations are some of the factors that have driven the marginal logger out of business and forced those that remain to take a careful look at their operations.

The picture is not entirely negative—especially for innovative operators. A technological edge exists for those who are willing and able to exploit it. One realization of this technological edge comes in the more efficient use of existing capital and labor resources.

Efficiency in timber harvesting starts with the design of the production facility, which at one stage might consist of laying out the individual setting to take maximum advantage of the available logging equipment and crews. Determining each landing location and placing boundaries for the setting are essential elements in this process. In order to accomplish this task the forest engineer must be familiar with the harvesting systems that are available if only to determine what is feasible and what is not based on mechanical analyses.

Mechanical feasibility is the primary, and often the only criterion applied to cable setting design. Scant attention has been explicitly given to harvesting economics in the PNW since little was needed in its restrictive mountainous terrain where typical logging practice was to clearcut and high-lead yard all merchantable timber. This general indifference to the economics of timber harvesting during the last century has been punctuated by an occasional impulse of interest when the economic viability of the industry was seriously threatened as, for example, it was during the Great Depression. Today the immediate threat is not to the industry as a whole but to the small, independent operator trying to successfully compete within the contemporary economic milieu. In the longer term, however, the economic health of the forest products industry in the PNW will depend not only on the competitive advantage it enjoys in timber growing but also its relative economic advantage in cutting, processing, and transporting logs from woods to market. Whether the forest engineer works for the timberland owner or the contract logger it is to the economic advantage of both parties to identify and employ the most costeffective means of timber harvest and transport.

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One purpose of this paper is to encourage forest engineering practitioners and associated analysts to more aggressively employ economic decision criteria in cable setting design. In this regard modern computing technology facilitates the use of several new analytical concepts that can be effectively used to describe some important characteristics of cable settings. The application of these concepts to the economic analysis of cable settings will be demonstrated using examples taken from the literature.

HIGH-LEAD VERSUS SHOTGUN YARDING

Many of the high-lead yarder/towers commonly encountered in the PNW can be rigged as something other than a high-lead cable configuration. For example, it is not uncommon to find a logging show where the logger will configure his equipment as either a high-lead or shotgun system depending on yarding conditions (McGonagill 1978). In the example presented here, the relative advantages of these two alternative cable configurations will be compared. Two descriptive measures of the setting, average external yarding distance (AEYD) and average yarding slope (AYS), will be used in making this comparison. In order to effectively illustrate and manipulate these two parameters a convenient archetypical halftree (yarding through 180 degrees) cable setting is conceptualized as illustrated in figures 1 and 2. All other setting parameters will be specified and held constant throughout this analysis although it is understood that these also might be varied and their impact on alternative cable configurations compared.

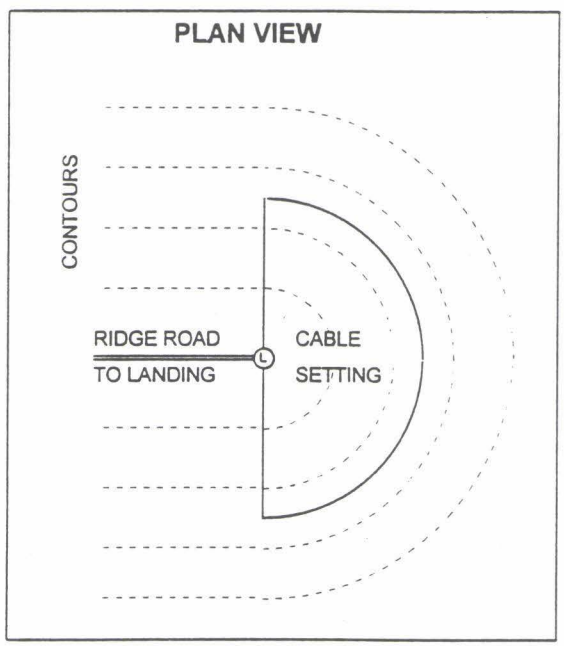

Figure 1.—*Aerial view of the setting.*

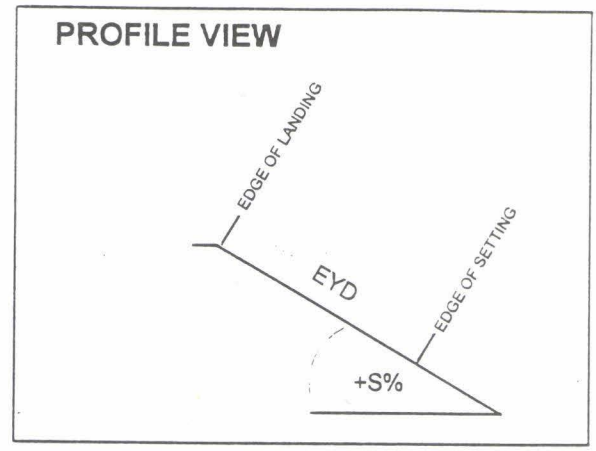

Figure 2.—*Cross-sectional view of the setting.*

For more realistic illustrative purposes, the published results from two exceptionally welldone cable time studies will be used. The cycle time equation for high-lead yarding is taken from Tennas *et al.* (1955) and the shotgun cycle time equation is based on one developed by Gibson (1975). Interested readers are referred to these two publications for specific details regarding the equations. It is worth emphasizing that these two cycle time equations were developed for very different machines and crews, not to mention a multitude of other distinctly different factors of operational significance, so that no comparative conclusions can be definitively drawn from the results now to be presented—**only a suggested process of analysis and system comparison is being outlined in this paper.**

The high-lead yarding cycle time equation of Tennas *et al.* is used without modification in obtaining the results that follow. The cycle time equation, of the form $y=\exp[f(x_1,x_2,,,)]$, given by Gibson for shotgun yarding was approximated with a power series expansion discarding all terms of second order and greater. A very close approximation to Gibson's original equation was observed over the domain of interest.

For the high-lead system the cable road width (average distance from one tailhold block to the next) was set at 75 feet with an average time per road change of 12 minutes. For the skyline system the average road width was set at 150 feet with an average road change time of 64.2 minutes. Delay was estimated as 14 percent of scheduled operating time for both cable configurations and assumed equally applicable when either yarding or changing roads. The fixed movein/moveout time was set at 720 minutes and assumed to be done outofshift. No delay factor was applied to this fixed time element and it was added to the scheduled operating time of each system before making the final time per unit of output calculation.

Other fixed parameters for this comparison were: 150 logs per acre, 300 board feet per log, 3.3 logs per turn, and 2 choker setters (there is also a rigging slinger). These parameters were essentially the same for both the high-lead and shotgun systems. By somewhat arbitrarily maintaining a common parameter set for both cable configurations the issue of costing out the systems has been sidestepped, at least for this specific illustrative example. The cost evaluation of each system is quite straight forward, but owner specific, and its insertion here would not serve the primary purpose of the paper.

In order to compare the two cable configurations, the external yarding distance and yarding slope of the archetypical halftree setting are varied. The total volume on the setting and the total time required to log that volume using each system are calculated. Consider the following numerical example. If the external yarding distance is 750 feet and the yarding slope is 20 percent on the setting then the following setting parameters are readily calculated: 500 feet for average yarding distance (AYD), 20 percent for average yarding slope (AYS), 281,250 feet-squared for expected square of the yarding distance (ED2), 400 percent-squared for expected square of the yarding slope (ES2), 10,000 feet-percent for expected product of yarding distance times slope (EDS), 2,310 feet for the effective external boundary (EEB), and 19.50 acres for the setting area. With these parameters the expected high-lead cycle time is 5.92 minutes and the shotgun cycle time 7.19 minutes. The average lateral yarding distance (ALD) for the skyline (25 feet) is based on the average road width for that system. The expected number of yarding cycles required over the entire setting may be estimated from the total number of logs on the setting and the average number of logs per turn. The total productive time spent changing cable roads is calculated by multiplying the number of cable roads on the setting (estimated by dividing the EEB by the average road width for the system being examined) by the average time expended per road change. Total productive time spent yarding and changing cable roads is then divided by one minus the ratio delay (0.86). This last calculation yields the total scheduled operating time estimate. The fixed time is added to give the final time estimates for this example: 7,248 minutes for the high-lead and 9,280 minutes for the skyline system. The final result is presented in time per unit of output: 8.26 minutes per Mbf for the high-lead and 10.57 minutes per Mbf for the skyline. All of these calculations are readily done for a variety of different parameter values using a spreadsheet.

The results of such a spreadsheet analysis are shown graphically in figures 3 and 4. These two figures confirm and perhaps even expand our understanding of cable system performance. It is observed for example that in the case of both systems there is an external yarding distance that will minimize the time per unit of output for a setting with a given yarding slope. This optimal relationship between distance and slope is plotted in figure 5 as a separate curve for each system. Not unexpectedly, the performance behavior of the two systems with respect to changing slope is fundamentally different. High-lead productivity is adversely affected by increasing slope while shotgun productivity rises with increasing slope—a consequence of its gravity outhaul design. An examination of productivity change with increasing external yarding distance also shows interesting but not unanticipated characteristics of each system. The high-lead system is quite sensitive to yarding distance and shows a welldefined trough in its performance surface. While shotgun system productivity initially shows extreme sensitivity to changes in distance (at short external yarding distances) its performance eventually becomes almost insensitive to changes in distance at the longer external yarding distances—once again a consequence of its gravity outhaul design where at greater distances the continued accelerating force of gravity more than compensates for initially low carriage velocities near the landing.

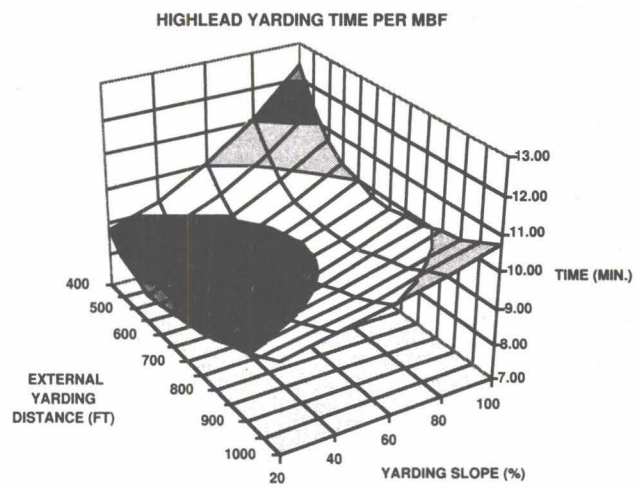

Figure 3.—*Performance surface for the high-lead cable configuration.*

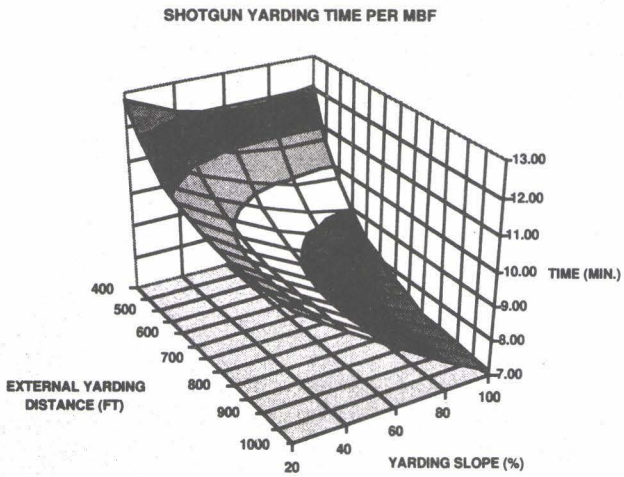

Figure 4.—*Performance surface for the shotgun cable configuration.*

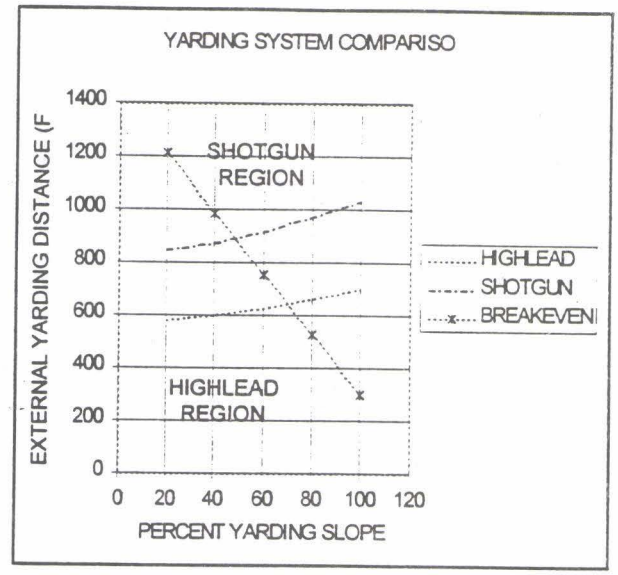

Figure 5.—*Yarding system niche by slope and distance.*

These figures are obviously useful in and of themselves, but perhaps of even more interest are the comparisons that they afford between the two systems. One such comparative evaluation can be summarized by examining the space curve formed by the intersection of the two surfaces of figures 3 and 4. Because of the fundamentally different system responses to increasing slope a very "stable" curve is obtained. A planar projection of this space curve is shown in figure 5 where it divides the distance-slope domain into two regions—one in which the most productive system is the high-lead and a second where the shotgun is more productive. The "stability" of this curve with respect to its projected location onto the distance-slope plane is due to the angles at which the two performance surfaces intersect; changes in height (performance) of either or both surfaces do not significantly shift the position of the projected curve. Another consequence of these angles is that using the wrong system even within a short distance of the boundary between the two regions will seriously reduce production below what it could be if the correct cable configuration were used. While the reader is once again cautioned regarding specific conclusions based on these two performance surfaces it would certainly appear warranted to conclude that the potential exists to develop curves for individual operations that could be of very substantial practical value to the logger as well as the forest engineer.

Other archetypical cable settings might be developed that more closely match the typical logging chance of an area. Two obvious possibilities would be half and fulltree settings on a uniform sidehill slope. One advantage of generalized setting models of this type is the ready development of graphs (fig. 5) or even easily remembered rules of thumb extracted from such graphs; either of which can provide users with a quick indication of what might be the most appropriate yarding equipment for a particular site.

The paper logging plan of the practicing forest engineer is now developed within a datarich computerized planning environment. There is little reason for the planner to rely solely on rules of thumb in setting design when computer estimates more firmly based on the available data can be easily programmed. The next example shows a higher level of setting design analysis although certainly not the highest currently available. Once again particular attention will be directed toward finding and using setting parameters such as EEB and AEYD which can play key roles in the more accurate calculation of yarding system productivity.

HIGH-LEAD LANDING PLACEMENT EVALUATION

In this example the published results of the time study by Tennas *et al.* (1955) are once again employed. A hypothetical setting described by Greulich (1992) was selected for evaluation. With the exception of logs per acre which is changed to 200 and volume per log which is now set at 500 board feet the yarding conditions remain the same as in the previous example. The design objective in this case is to examine two alternative landing locations with respect to their relative yarding costs. The shape of this particular setting is irregular and calculation of the EEB and AEYD would be quite tedious without computer assistance. Accordingly a program was written to first identify the external yarding boundary and then subsequently calculate these two setting parameters.

Once the line segments comprising the external yarding boundary have been identified the EEB and AEYD are readily calculated for each component line segment using formulas provided elsewhere (Greulich 1987). The EEB for the entire setting is then quite simply the sum of the EEBs of the individual segments. The AEYD for the setting is calculated as the EEBweighted grand mean of the segment AEYDs. The two alternative landing locations for this setting were evaluated in this fashion and the calculated setting parameters are shown in tables 1 and 2. The line segments comprising the external yarding boundary for each landing location are also listed. These boundaries are plotted in figures 6 and 7 for the two alternative landing locations.

A spreadsheet was then used to evaluate high-lead performance at each of the two alternative landings. The first landing location has a shorter EEB than the second so that only 269 minutes of productive time are expended in cable road changes associated with that landing. The second landing requires 394 minutes of productive time in road changes but that additional time is easily compensated for by its more central location (evidenced by its shorter AYD). In the final analysis the times per unit output are 5.75 and 4.71 minutes/Mbf for the first and second landing locations, respectively. The lower yarding cost associated with the second location might ultimately justify its selection but the costs associated with the additional length of access road would also be considered before any choice were made.

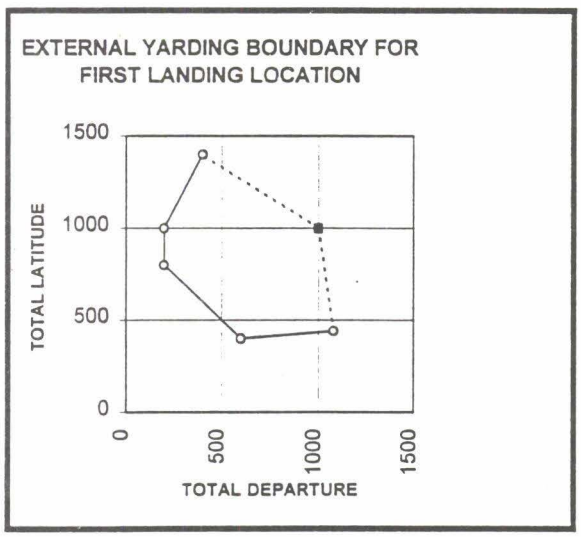

Figure 6.—*External yarding boundary, alternative landing location one.*

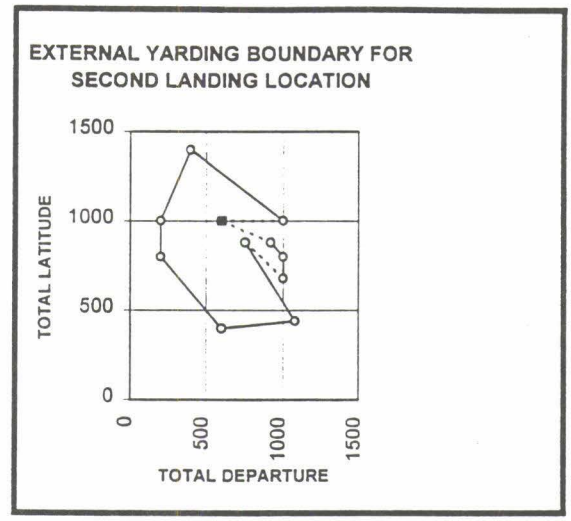

Figure 7.—*External yarding boundary, alternative landing location two.*

CONCLUDING STATEMENT

The external yarding boundary and its measure, the EEB, provide a rational basis for estimating the total number of cable roads required to yard a setting as well as their expected, or average, length (AEYD). Here it has been illustrated how the EEB might be employed to more realistically describe and evaluate cable yarding productivity. The concept and its application were illustrated with two examples. In the first, the EEB was incorporated into a spreadsheet program where yarding productivity of two alternative cable configurations were analyzed for a generic setting layout. The results of this particular analysis strongly suggest that the evaluative procedure is descriptively accurate and that useful numerical results might be easily developed and summarized in graphical form. In the second example a setting with an irregular boundary was evaluated for two alternative high-lead landing locations. A computer program was used to calculate the EEB for subsequent spreadsheet evaluation of yarder productivity. In contrast to the idealized generic setting layout of the first example, site specific conditions are here modeled in considerably more detail. This increased layout detail provides the analyst with the opportunity to more accurately estimate the economic impact of the many irregular designs now being suggested for setting layouts in the PNW.

Table 1.—*Computer program output for first landing location*

LANDING COORDINATES:		X_0	Y_0	Z_0
		1000.	1000.	1000.
TURNING POINT NUMBER & COORDINATES:	i	X_i	Y_i	Z_i
	1	1000.	1000.	1000.
	2	400.	1400.	640.
	3	200.	1000.	840.
	4	200.	800.	780.
	5	320.	920.	840.
	6	360.	1000.	872.
	7	400.	1080.	832.
	8	400.	1000.	880.
	9	400.	920.	856.
	10	320.	920.	840.
	11	200.	800.	780.
	12	600.	400.	740.
	13	1080.	440.	848.
	14	720.	920.	920.
	15	920.	880.	948.
	16	1000.	680.	904.
	17	1000.	800.	940.
	18	920.	880.	948.
	19	720.	920.	920.
	20	600.	800.	860.
	21	400.	800.	820.
	22	600.	1000.	920.
SETTING PARAMETERS:				
TOTAL YARDED AREA OF THE SETTING:	444800.			
AVERAGE YARDING DISTANCE:	557.			
AVERAGE YARDING SLOPE:	33.			
EXPECTED SQUARE OF YARDING DISTANCE:	336253.			
EXPECTED SQUARE OF YARDING SLOPE:	1142.			
EFFECTIVE EXTERNAL BOUNDARY:	1683.			
AVERAGE EXTERNAL YARDING DISTANCE:	750.			
EXTERNAL YARDING BOUNDARY VECTORS:				
	X1,Y1,Z1:	400.	1400.	640.
	X2,Y2,Z2:	200.	1000.	840.
	X1,Y1,Z1:	200.	1000.	840.
	X2,Y2,Z2:	200.	800.	780.
	X1,Y1,Z1:	200.	800.	780.
	X2,Y2,Z2:	600.	400.	740.
	X1,Y1,Z1:	600.	400.	740.
	X2,Y2,Z2:	1080.	440.	848.

Table 2.—*Computer program output for second landing location*

LANDING COORDINATES:		X_0	Y_0	Z_0
		600.	1000.	920.
ETTING PARAMETERS:				
TOTAL YARDED AREA OF THE SETTING IS:	444800.			
AVERAGE YARDING DISTANCE IS:	347.			
AVERAGE YARDING SLOPE IS:	30.			
EXPECTED SQUARE OF YARDING DISTANCE IS:	141811.			
EXPECTED SQUARE OF YARDING SLOPE IS:	1229.			
EFFECTIVE EXTERNAL BOUNDARY IS:	2461.			
AVERAGE EXTERNAL YARDING DISTANCE IS:	455.			
EXTERNAL YARDING BOUNDARY VECTORS:				
	X1,Y1,Z1:	1000.	1000.	1000.
	X2,Y2,Z2:	400.	1400.	640.
	X1,Y1,Z1:	400.	1400.	640.
	X2,Y2,Z2:	200.	1000.	840.
	X1,Y1,Z1	200.	1000.	840.
	X2,Y2,Z2:	200.	800.	780.
	X1,Y1,Z1:	200.	800.	780.
	X2,Y2,Z2:	600.	400.	740.
	X1,Y1,Z1:	600.	400.	740.
	X2,Y2,Z2:	1080.	440.	848.
	X1,Y1,Z1:	1080.	440.	848.
	X2,Y2,Z2:	750.	880.	914.
	X1,Y1,Z1:	1000.	680.	904.
	X2,Y2,Z2:	1000.	800.	940.
	X1,Y1,Z1:	1000.	800.	940.
	X2,Y2,Z2:	920.	880.	948.

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ANALYSIS OF ROAD LOCATIONS IN WETLANDS AND MITIGATION BANK DEVELOPMENT

Joseph P. Roise and Kevin W. Gainey[1]

ABSTRACT.—The problem posed is to create a spatial analysis tool that will allow transportation planners to minimize road impacts to wetlands while maximizing mitigation returns. Using a regional wetland rating system, we incorporated wildlife habitat, nonpoint source pollution reduction, and floodwater storage functions into a mixed integer formulation to determine an optimal combination of mitigation sites. These functions will be driven by a geographic information system. A lack of quantitative data and meeting regulatory requirements are the two issues of concern when developing wetland models.

INTRODUCTION

The purpose of our work is to find a way to improve the transportation planning process by including wetland functions in a spatial analysis tool. Wetlands are a part of the natural landscape that have been the subject of countless scientific and legislative debates. Evolving from these debates, federal and state policies require that impacts to or degradation of a wetland be mitigated for, meaning that wetland losses must be replaced. Transportation improvements and construction impact wetlands when projects intrude into low-lying, flat areas, making transportation agencies one of the largest destroyers of wetlands (Anonymous 1994). The process of mitigation can be *ad hoc*, in that there is no good tool for finding possible mitigation sites where the wetland replacement is based on functions instead of acreages. Wetland functions are the ecological processes that occur in these systems. For example, the ability of a wetland to provide nesting habitat for waterfowl is a function. Groundwater recharge, pollutant removal, and floodwater storage are other wetland functions. These functions should not be used as synonyms for wetland values, that is, the importance that society assigns to wetland functions. A wetland may play a large part in removing sediment and pollutants from a city's water supply, and therefore, be valuable to the city. However, wetlands with the same functions but not directly affecting the water supply may not be as valuable to the city.

Wetlands were once pervasive in the coastal plain of North Carolina but draining and development have converted many sites to agricultural fields, pine plantations, road corridors, and urban areas. Because the societal and ecological values of wetlands have been emphasized in recent decades, there is a desire to better protect existing wetlands. Population growth, which requires larger transportation systems, heightens the impact of humans on the environment. Wetland restoration is the primary method by which road impacts are mitigated. Wetland restoration is simply taking an area that was once a wetland but has been developed and converting it back to a wetland. This may require restoring vegetation, hydrology, and some soil characteristics to pre-disturbance levels, if possible.

The North Carolina Department of Environmental Health and Natural Resources' Division of Coastal Management (DCM) has developed a wetland mapping and functional assessment initiative for the 20 coastal counties within their jurisdiction (Sutter and Wuenscher 1997). This assessment method, titled North Carolina Coastal Region Evaluation of Wetland Significance (NC-CREWS), is a procedure based on spatial data layers contained in a geographic information system (GIS). This paper looks at the development of wetland function models using NC-CREWS parameters, which will be linked to existing GIS databases developed by DCM. This tool will allow transportation planners to quickly analyze alternative road corridors, the accompanying impacts to wetlands, and possible sites to mitigate these impacts.

DESCRIPTION OF THE MODEL

NC-CREWS Functions

NC-CREWS looks at a variety of wetland functions, but only three will be considered in this first version of the model. Each function has a series of parameters that are combined to give each wetland unit in the GIS an overall

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rating for each function. The wetlands are rated High, Medium, or Low for the function being considered. The functions considered here are terrestrial wildlife habitat, nonpoint source pollution reduction, and floodwater storage.[2] The database developed by DCM contains these ratings for existing wetlands. Because the model looks at land units that could be converted to wetlands, these ratings must be calculated for each combination of land units chosen as alternatives satisfying the constraints.

Terrestrial Wildlife Habitat

This function is rated on the quality of habitat provided for terrestrial wildlife. The parameters considered are interior size, percent surrounding habitat that is natural vegetation, and the length of a wildlife corridor that links to other natural vegetation. To calculate interior habitat, a 100 meter buffer zone around the perimeter is subtracted from the total area (Sutter and Wuenscher 1997). The rating strategy for wildlife habitat parameters is shown in table 1.

Nonpoint Source Pollution Reduction

Three parameters of the nonpoint source rating system were considered. First, the proximity to agriculture, developed land, pine plantation, and natural vegetation are considered using the percent of surrounding habitat as the criteria. Second, the distance from a water source is used. Third, the position of the wetland relative to stream orders is used. Table 2 summarizes the rating scheme.

Floodwater Storage

The position of the wetland in the landscape, the duration of flooding, and the width of the wetland perpendicular to the stream are the parameters considered for rating the floodwater storage capacity of a wetland. Table 3 summarizes floodwater storage rating criteria.

Methods and Assumptions

To make the NC-CREWS rating method work in a model, values had to be assigned to the rankings of High, Medium, and Low. The rankings were treated as indices and were assigned integer values of 1, 2, and 3 (Low, Medium, and High). The acreage of the wetland is multiplied by the rating for each parameter in the three functions and combined to produce a cumulative, numerical ranking that represents functional units supplied by the wetland.

[2] *All functions and parameters are taken from the NC-CREWS manual by Sutter and Wuenscher (1997).*

Table 1.—*Ratings assigned to wildlife habitat parameters*

Parameter	High rating	Medium rating	Low rating
Interior size	> 74 acres	0–74 acres	None
Surrounding habitat	> 50% wetlands	< 50% wetlands	Isolated from other wetlands
Wildlife corridor	> 600 feet	< 600 feet	Isolated from natural habitat

Table 2.—*Ratings assigned to nonpoint source pollution parameters*

Parameter	High rating	Medium rating	Low rating
Proximity to sources	> 50% perimeter agriculture + developed	> 50% perimeter agriculture + developed + pine plantation	> 50% perimeter natural vegetation
Distance to water source	Within 300 ft. of Permanent source	Within 300 ft. of intermittent stream	> 300 ft. from permanent or intermittent source
Wetland position	Intermittent or 1st order stream	2nd or 3rd order stream	Higher than 3rd order stream

Table 3.—*Ratings assigned to floodwater storage parameters*

Parameter	High rating	Medium rating	Low rating
Position in landscape	> 25% stream bordered by developed land	5–25% stream bordered by developed land	<5% stream bordered by developed land
Duration of flooding	Long to very long	Brief	Very brief
Width of wetland perpendicular to stream	> 100 feet	50–100 feet	< 50 feet

The generalized steps that the model employs are:

1. The total functional units existing in a watershed where a road is planned are calculated using the NC-CREWS GIS procedure.
2. The user indicates a transportation corridor by adding the link to an existing road network.
3. For links impacting wetlands, the functional units are recalculated to measure the number of units lost to the road addition.
4. The mixed integer model is run to find the optimal combination of land units to be converted to mitigation sites.

In order to make a workable model based on NC-CREWS that would be usable in a GIS environment, several key assumptions have been made:

1. All of the parameters and functions are equally weighted.
2. There is no requirement that specific parameter units removed by a corridor must be replaced by the same parameters in the mitigation sites. Only the total number of functional units must be replaced. For example, the number of habitat units destroyed must be replaced by habitat units, and likewise for nonpoint source and flood storage units.
3. Within the GIS layers, only entire sites may be considered for mitigation. No portion of a possible site may be used.

The Model

Following the above procedure and using the listed assumptions, the linear programming model has the form:

$$\text{Maximize: } A^TX(F_{Hab} \times R_{Hab} + F_{NPS} \times R_{NPS} + F_{FS} \times R_{FS} - c) - C_{Road} - (F_{Hab})(H_{Loss}) - (F_{NPS})(NPS_{Loss}) - (F_{FS})(FS_{Loss})$$

$$\text{Subject to: } R_{Hab}A^TX \geq H_{Loss}$$
$$R_{NPS}A^TX \geq NPS_{Loss}$$
$$R_{FS}A^TX \geq FS_{Loss}$$
$$C_{Road} + cA^TX \leq C_{Max}$$

Where: A_i = acreage for land unit i for i = 1...n with n land units in study area

X_i = [0,1] decision variable to convert land unit i to wetland, i = 1 to n

F_{Hab} = scalar conversion factor of a habitat functional unit to dollars

F_{NPS} = scalar conversion factor of a nonpoint source functional unit to dollars

F_{FS} = scalar conversion factor of a floodwater storage functional unit to dollars

R_{Hab} = sum of ratings for habitat parameters, integer in [3..9]

R_{NPS} = sum of ratings for nonpoint source parameters, integer in [3..9]

R_{FS} = sum of ratings for floodwater storage parameters, integer in [3..9]

c = cost per acre of converting land to wetland

C_{Road} = cost of constructing road corridor

H_{Loss} = habitat functional units lost to road corridor

NPS_{Loss} = nonpoint source functional units lost to road corridor

FS_{Loss} = floodwater storage functional units lost to road corridor

C_{Max} = maximum dollar value available for road and mitigation project.

The constraints for nonpoint source and floodwater storage are based only on the total area of the land units when calculating functional units. However, when calculating functional units for interior habitat, if adjacent land units are chosen, the amount of interior habitat will increase because portions of the 100 meter buffer will become interior space. For each iteration of the program, R_{Hab} must be recalculated. This will be done by the GIS database accompanying the NC-CREWS system.

The last four terms of the objective function are costs incurred from road construction and do not depend on the combination of possible mitigation sites. For a single road corridor alternative, these terms may be dropped from the objective function and the maximum mitigation return can be calculated. The terms have been included in

the equation for clarity and to support the need for transportation planners to analyze alternative corridors.

An Example Using Habitat Functions

The following example uses only the habitat function to determine an optimal mitigation combination for a given road corridor. Visual display of nonpoint sources and floodwater storage models becomes difficult without a GIS since hydrology and land use data layers must be used together. Figure 1 shows the pre-road watershed and table 4 contains the corresponding acreage information. After unavoidably placing part of a road through a wetland (fig. 2) mitigation combinations must be calculated.

The road added to the watershed splits X1 into two new land units, creating X6. X6 has an area of 22.5 acres, with interior space occupying 10 acres. The shaded area represents the 100 meter buffer around the road where the impacts occur. The undisturbed watershed contained 750 functional units. Adding the road destroyed 390 units that must be mitigated for. Table 5 shows the user defined constants used in this example.

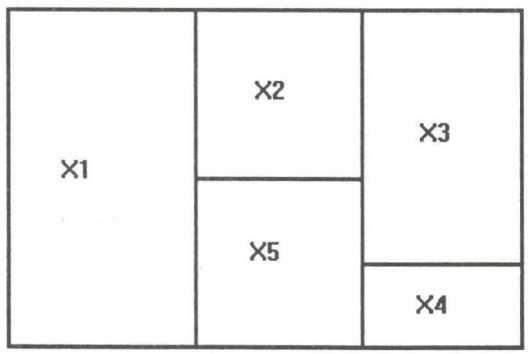

Figure 1.—*Simplified arrangement of land units in a watershed where road impacts will require mitigation.*

Table 4.—*Characteristic of example watershed*

Land unit	Land use/ Land type	Total acres	Interior acres
X1	Wetland	150	80
X2	Pine Plantation	62.5	22.5
X3	Pine Plantation	70	25
X4	Pine Plantation	30	5
X5	Pine Plantation	62.5	22.5

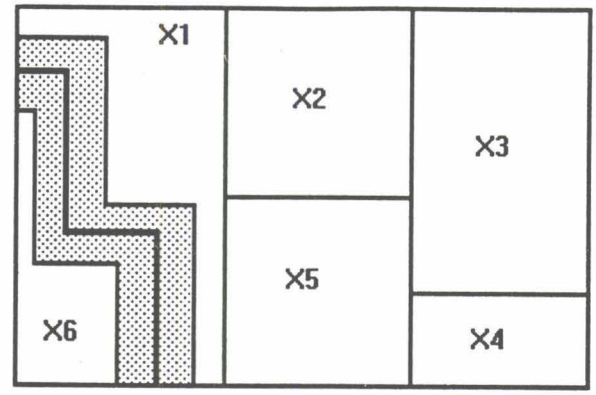

Figure 2.—*Example watershed with added road that requires mitigation.*

Table 5.—*User defined constants for example*

Constant	Value
	$
F_{Hab}	2
F_{NPS}	2
F_{FS}	2
c	20

When using the algorithm only with the habitat function, the optimum combination of land units to restore to wetlands is X2 and X5. Table 6 shows the functional units and mitigation returns possible from all combinations of X2, X3, X4, and X5. X6 remained wetland and obviously cannot be used for mitigation credit.

This example shows the optimum combination of mitigation sites in terms of financial outlay. Using the figures given in table 5, meeting the constraints results in a financial loss. Depending on the choices of F_{Hab}, F_{NPS}, and F_{FS}, it is possible that the optimum objective function value could be positive.

DISCUSSION AND CONCLUSIONS

Because of the varying opinions of wetland functions and assessment methods, this project used only the NC-CREWS system to drive the models. This system was developed for a specific geographic region to which this model is currently limited. Because most wetland rating systems try to attach numbers to wetland functions, this model, because of its simplicity, could easily be modified to meet needs in regions other than the coastal plain of North Carolina.

Table 6.—*Functional units gained from possible mitigation site combinations*

Land unit combination	Total area of wetlands in watershed	Watershed functional units	Units gained from mitigation sites	Objective function value [a]
	acres			*dollars*
X2	130	610	250	NA
X3	70	565	205	NA
X4	30	405	45	NA
X5	130	610	250	NA
X2 + X3	200	1090	730	-400
X2 + X4	160	740	380	NA
X2 + X5	**192.5**	**1052.5**	**692.5**	**-385**
X3 + X4	167.5	760	400	-670
X3 + X5	200	890	530	-800
X4 + X5	160	730	370	NA
X2 + X3 + X4	230	1240	880	-460
X2 + X3 + X5	262.5	1402.5	1042.5	-525
X2 + X4 + X5	222.5	1202.5	842.5	-445
X3 + X4 + X5	230	1172.5	812.5	-595
X2 + X3 + X4 + X5	292.5	1552.5	1192.5	-585

[a] Does not include last four terms of the objective function which are constants. NA denotes infeasible solution.

The next step in this process is to attach the model to a GIS. Using macros and custom designed interfaces, the ideal tool would require the user to enter the watershed being impacted, the road corridor (through on-screen digitizing), costs associated with construction and mitigation, and values for F_{Hab}, F_{NPS}, and F_{FS}. GIS procedures of buffering, overlay, and dissolving boundaries will be used to obtain the required values for each model iteration. Further work will focus on adding more functions and parameters to the model.

As with any complicated ecosystem, the model is only as good as the available input data. There is a wealth of quantitative data, but no one seems to know which numbers are correct and which are not, especially in light of current regulations and changing societal values. Because wetland mitigation is performed on an acre basis using policy defined ratios for restoration, this model is different in that it has no size requirements. The focus is purely on replacing functional units. As Kulkarni and others (1993) noted, any time you use values that denote tradeoffs (F_{Hab}, F_{NPS}, and F_{FS}), some subjectivity is introduced. This subjectivity cannot be avoided since quantitative measures of wetland values do not exist. As wetlands become better understood and the driving forces behind functions are viewed within the context of the entire watershed the model will need to be revised.

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OPTIMIZING STAND LEVEL FOREST HARVESTING USING A TRADEOFF OBJECTIVE FUNCTION

Eldon A. Gunn and Evelyn W. Richards[1]

ABSTRACT.—We have developed a tabu search method to optimize the stand level harvest decision over intermediate time frames (10-30 years) within the context of a longer term hierarchical plan. In this paper, we focus on the objective function for our model. We are interested in the trade off between two main issues, one the cost of building roads to access the resource and the other the loss of forest productivity when stands are harvested too early or too late. We develop a biological productivity loss function and show how to examine the trade offs between the cost of roads and the productivity losses.

INTRODUCTION

In this paper, we address the problem of optimizing the stand harvest schedule for medium-range tactical planning, while meeting volume requirements in each period as specified by a previously executed strategic planning process. We assume that accessing stands in the forested area will require some road building, and that, consequently, a network of potential road links has been designed to cover the area. Although many tactical level objectives are worth considering, we will concentrate on the minimization of two costs. The first is the negative impact on long-term forest productivity caused by harvesting stands either too early or too late. The second is the cost of building roads to access the stands to be harvested.

These cost factors are in opposition, since improving the timing of harvests can only be done by increasing the investment in road building. We do not assume, however, that the decision-maker has fixed a road building budget or a tolerance level for lost productivity. Instead, we produce a spectrum of solutions to the scheduling problem which range from those with very little road building to those where a high investment in road construction is required. By then recording the non-dominated solutions, we produce an efficient frontier or trade off curve which clearly presents the trade off effect over the range of road budget decisions which are available.

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Our model is constrained to meet maximum opening size and adjacency delay constraints. We do not assume that the adjacency delay period is equal to one planning period. The spatial decision unit is the stand, avoiding pre-blocking of stands. We use a Tabu Search metaheuristic to solve the model.

This paper is organized as follows. In section 1 we describe the planning problem and the model. In section 2 we describe the basic solution philosophy and technical issues in dealing with adjacency constraints and the road network. In section 3 we present some results, which were obtained from a forest coverage of a region of Cumberland County, Nova Scotia. Section 4 concludes with some conclusions and discussion.

THE PLANNING PROBLEM

This problem is to optimize decisions made at the tactical level of forest planning. The tactical planning problem is considered in the context of a hierarchical forest planning system (Weintraub and Davis 1996, Weintraub and Cholaky 1991, Gunn and Rai 1987), where the strategic planning process has been previously executed. The strategic planning exercise has used a long planning horizon and, amongst other goals, has enforced the requirement that production levels be consistent with sustained yield. One result of this process is the recommendation of achievable levels of sustainable wood harvest over some longer planning horizon Then, the tactical planning problem is to produce a spatially explicit schedule of stand harvests and road building. This schedule must meet the strategic goals on volumes. It is further constrained to meet maximum opening size restrictions and adjacency delay constraints. In the IRPM formulation (Kirby *et al.* 1980), as in many other models

in the literature, the objective function is to maximize net present value accruing from the periodic flows of wood products. We take a different approach. We assume that harvest levels, as determined by the strategic planning process, have already been maximized in the aspatial model subject to suitable constraints. Thus, achievable levels of production are already optimized. In our model, we restrict our attention to minimizing negative impacts on forest productivity due to timing of harvests and the costs of road construction, and constrain the model to meet the recommended production levels for each period. The harvest schedule is also constrained to meet maximum opening size and adjacency delay regulations on clearcuts. This framework for our model is illustrated in figure 1.

Volume Flow Constraints

Let TV, PV_j and dTV, dPV_j be the total and periodic volume targets and their allowed deviations, V_{sj} the volume flow from harvesting stand s in period j, J the number of planning periods and x_{sj} an indicator variable for harvesting stand s in period j. Then, the constraints on total and periodic volume flows are:

$$(1)\ \left|\sum_j\sum_s V_{sj}x_{sj} - TV\right| \le dTV, \text{ and } \left|\sum_s V_{sj}x_{sj} - PV_j\right| \le dPV_j,\ j = 1,\ldots,J$$

We will use the S- vector $\boldsymbol{x}$ to indicate a given harvest solution, where each element x_s is the harvest period assigned to stand s. The assignment $\boldsymbol{x_s} = 0$ indicates that the stand was clearcut in the previous planning period, and $\boldsymbol{x_s} = J+1$ means that the decision is to defer harvest decisions to the future.

Spatial and Temporal Constraints on Harvest

The adjacency delay time or green-up period is defined in integer multiples of the planning period units. For our problem, planning periods are of duration 5 years and green-up or adjacency delay is 10 years (Province of Nova Scotia 1990). The elementary spatial decision unit is the stand, which is generally much smaller in area than the maximum opening size. We have evolved the following definitions so that the adjacency delay and maximum opening size constraints can be effectively specified using adjacency graphs.

Definition 1.1 The *forest adjacency graph* or forest graph $FG=(S, E)$ is a set of nodes S, one for each stand, and an edge e in E for each pair of stands which share a common boundary (or are a minimum distance apart).

Definition 1.2 The *adjacency delay time* ADT is the number of planning periods required for green-up on adjacent openings.

Definition 1.3

$$S_p(x) = \left\{s \mid x_s \in [p - ADT + 1, p]\right\},\ p = 1,\ldots,J$$

the set of stands scheduled within one adjacency delay "window".

Definition 1.4 $E_p(x)$ is the set of edges of E with both end-nodes in $S_p(x)$.

Definition 1.5 $F_p(x) = (S_p(x), E_p(x))$ is the sub-graph of FG induced by $S_p(x)$ and $E_p(x)$.

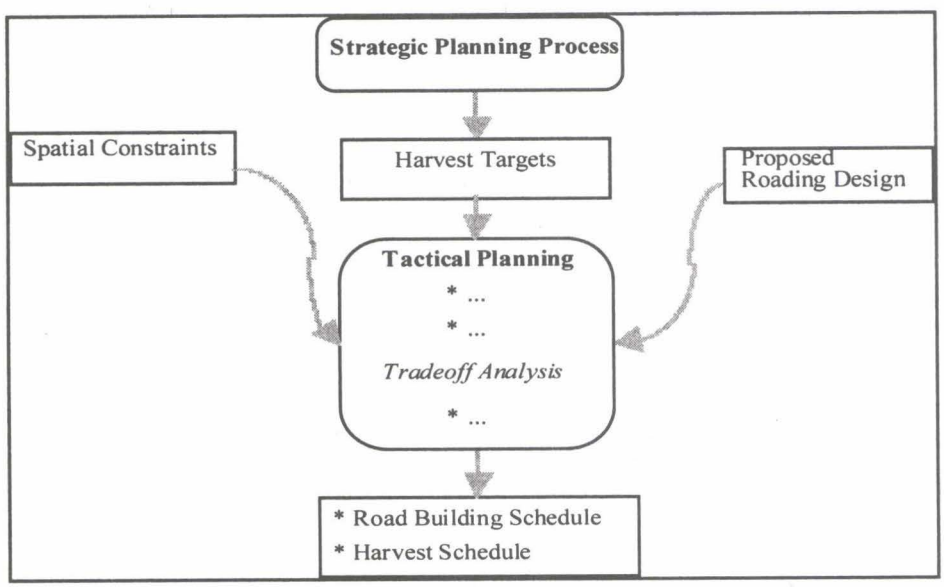

Figure 1.—*Model framework.*

Definition 1.6 An *opening* of period p $O_k^p(x)$ is a connected sub-graph of $F_p(x)$.

Figure 2 illustrates these openings for an *ADT* of two periods. Maximum opening size and adjacency delay requirements are then simultaneously enforced by requiring that each opening be of size less than or equal to *maxopen.*

(2) $\sum_{s \in O_k^p(x)} a_s \leq$ maxopen, k = 1,...,K^p(x), p = 1,...,J; a_s is the area of stand s.

Since the openings are dependent on a given harvest schedule **x**, there is no convenient method of specifying these constraints in an integer programming formulation. Enumeration of all potential openings which could cause a *maxopen* violation is possible, but not practical since the number of possible openings is exponential in the number of stands. However, the computational complexity of graph searches to calculate these openings is rather trivial in this application, since the forest adjacency graph is sparse. Thus, although this is not a useful model for integer programming methods, it will prove to be workable for our heuristic search methods.

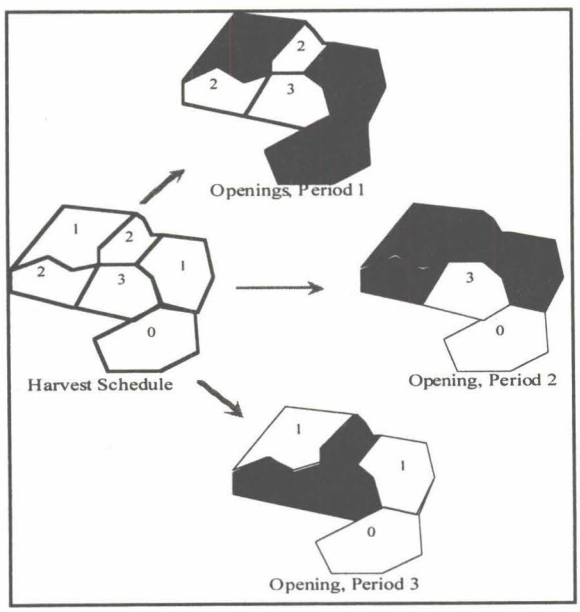

Figure 2.—*Multiperiod openings.*

Model Structure

In this problem the decisions are which stands to harvest, and when. We penalize the choice to harvest a stand at a period other than its peak productivity period using the Lost Volume penalty function *LV(s, j)*. The cost to build roads is determined by solving an induced road network design problem. These two cost factors are described in the following sections.

Lost Volume Penalty Function

The Lost Volume penalty function estimates productivity losses which are incurred by scheduling stands for harvest too early or too late. The mean annual increment, *mai(g),* of a stand at age *g* is the average wood volume increase per unit area per year at full stocking. For simplicity we will refer to *mai(g)* as *mai. Mai* depends on the existing cover type, age and site capability of the stand (Gunn 1994, Province of Nova Scotia 1993). Figure 3 shows *mai* curves for stands of site index 3 - 8 for Nova Scotia softwoods (higher numbered site index indicates better growth potential). If the biological production potential of the forest is to be maximized, then stands should be scheduled for harvest when they have reached their maximum *mai.* The lost volume penalty induced from assigning stand *s* to period *j* then is a function of the stand size, age, stocking, and *mai* and the current growth state of the stand. For *growing* stands the contribution to lost volume from assigning stand *s* to harvest in period *j* is

(3a) $LV_{growing}(si, j) = |mai\_\max(si) - mai(si, j)| \times a_s \times age_s(j) \times stocking,$

where *si* is the stand's site capability index, *j* is the harvest period, *age(j)* is the age at period *j*, a_s the acreage of stand *s* and *stocking* the percentage of full stocking on stand *s*.

For stands that have a significant amount of dead timber, we define a different lost volume function. The presumption is that the stand will resume normal growth after the inhibiting deadwood is removed and some remedial silvicultural action taken. Consequently, for *dead* stands, we penalize for each period that we wait to intervene.

(3b) $LV_{dead}(si, j) = \begin{cases} 0 & \text{if } j = 1 \\ \text{mai\_max(si)} \times (j-1) \times a_s \times \text{stocking} & \text{if } j \in [2, J+1] \end{cases}$

Thus, if the stand is cut in the first planning period, no penalty is applied, since this is the best action that can be taken. Otherwise, the delay to future periods is penalized by the expected future growth at maximum *mai*. The Lost Volume function is illustrated in figure 4, where stand *s* with the indicated *mai* curve is at age class 7 in period 1 of the planning horizon. The penalty for early harvest at period 1 and the penalty for late harvest at period 5 is illustrated in figure 4(a). If stand *s* were dead, the penalty to harvest (or treat) in period 4 is shown in figure 4(b).

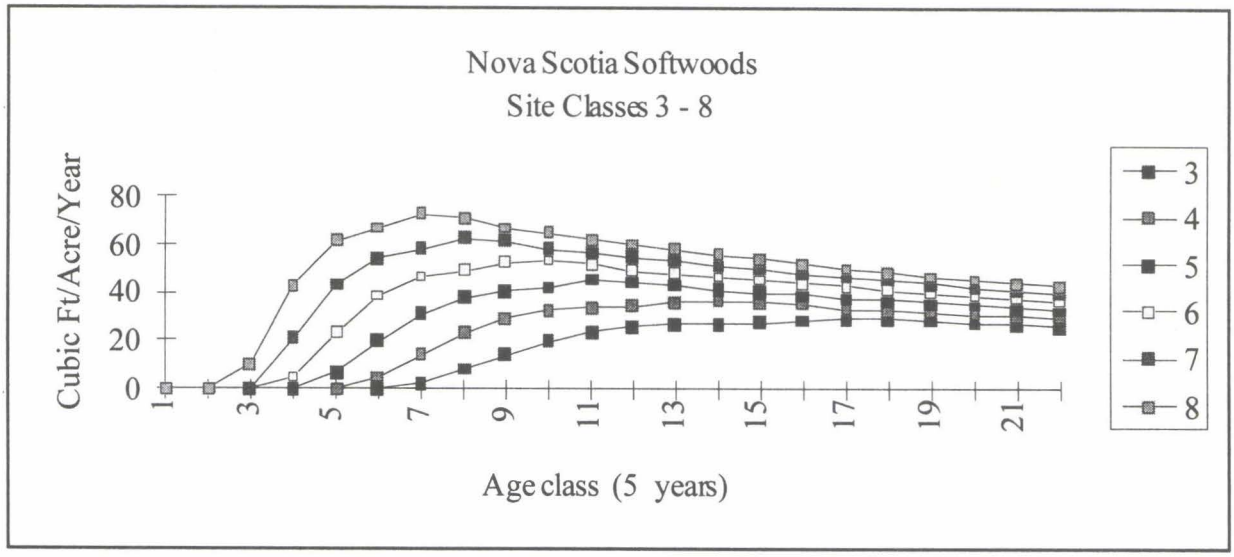

Figure 3.—*Mean annual increments.*

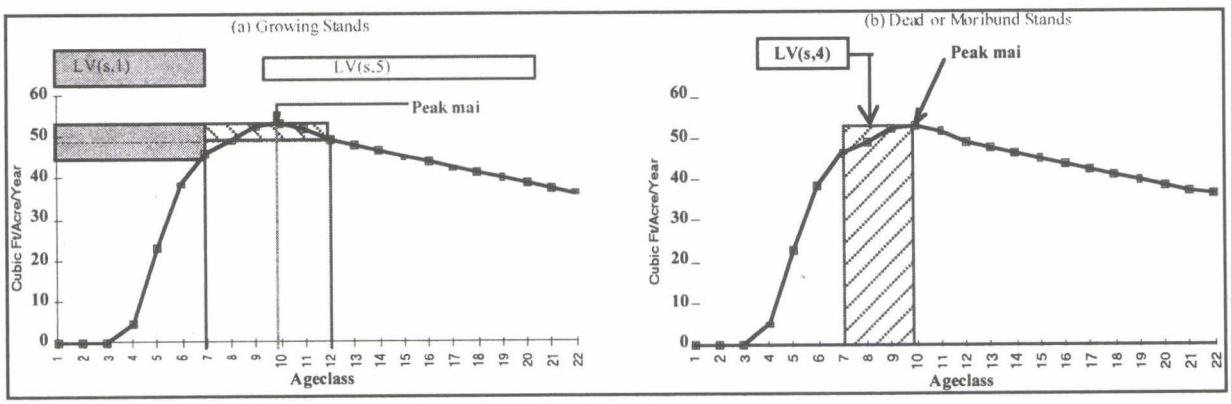

Figure 4.—*Lost volume function.*

Road Network

This network problem is based on an existing set of road links which cover the forest planning area. Figure 5(a) shows how a typical potential road network relates to stands and existing main roads. Multiple access points and cycles in the network are allowed, and each stand is accessed by one of the road links, or by a main road. For each link r, we associate the set S_r, consisting of all stands which require constriction of link r for access. Then, each harvest schedule $\boldsymbol{x}$ gives rise to a road network design problem, ***RNP(x)***.

The network is represented as a weighted graph $RG = (V, R, W)$, where the edges R are road links and each weight w_r is the cost to build link r. Vertices V are end nodes of the links, which are indexed in any unique fashion, with the proviso that only one node index is used to indicate that a link accesses a main road. That is, all existing main roads are "collapsed" into one node α.

For any harvest schedule $\boldsymbol{x}$, there is a set of required links $RL = \{r \in R | x_s \in [1, J], s \in S_r\}$. Each link in RL has an earliest required construction period $cp(r) = \min_{s \in S_r} \{x_s\}$. A feasible solution to ***RNP(x)*** is a directed connected subgraph $S(V', R')$ of RG such that there is a directed path in S $P_r = \{r, r_{n_1}, r_{n_2}, ..., r_{n_k}\}$ from each required link $\boldsymbol{r}$ in RL to α. That is, the ending link in this path, r_{n_k}, has one node equal to α. Each link in each path is assigned a construction period, a mapping Ω from R' into $[1, J]$ such that $\Omega(r_{n_k}) \leq \Omega(r_{n_{k-1}}) \leq ... \Omega(r_{n_1}) \leq \Omega(r)$. An optimal solution is one of minimum weight, i.e., one that minimizes the discounted costs of road building

$$\sum_{r|\Omega(r) \leq J} \frac{w_r}{(1+d)^{\Omega(r)}}$$

(d is the discount rate). If we restrict the problem to one period, or omit the discounting, it can be shown that it is equivalent to the Steiner Tree Problem on Graphs. Some special cases of STP are solvable in polynomial time, but in general the Steiner tree problem is NP-complete

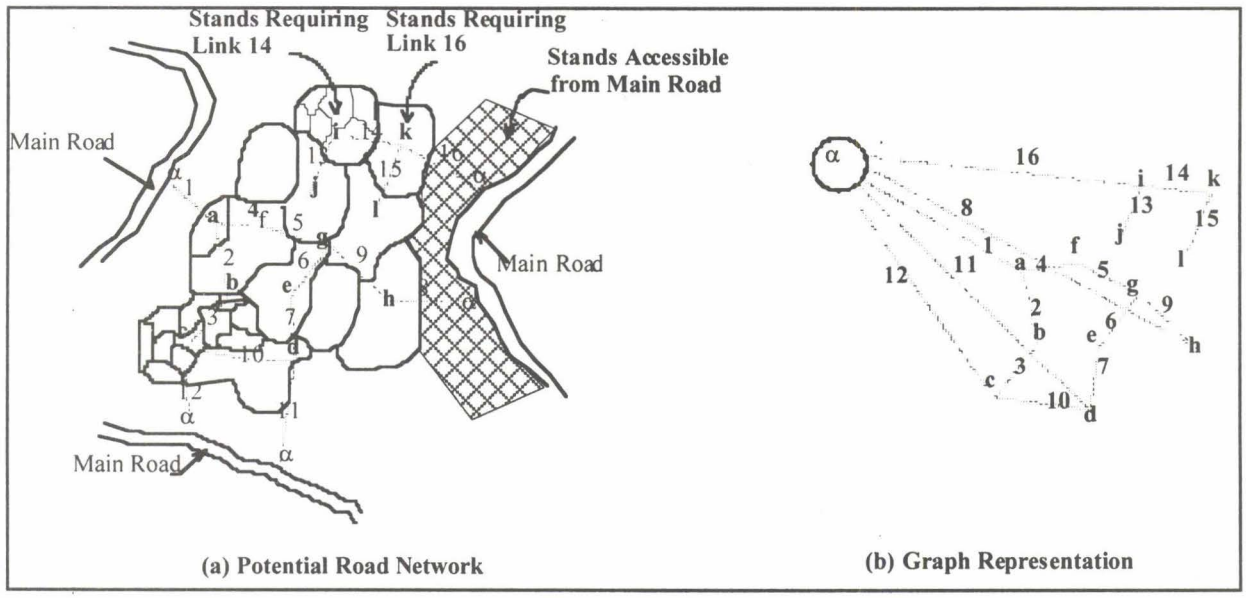

Figure 5.—*Road network.*

(Garey and Johnson 1979). Accordingly, we developed a heuristic method to solve ***RNP(x)*** (Richards 1997).

Model Objective Function

The model objective function is a parameterized sum of the lost volume penalty and the road construction cost. Using indicator variables x_{sj} and z_{rj} for harvesting stands and building roads in period j, the objective is

$$z(\rho) = \sum_{j=1}^{J+1}\sum_{s=1}^{S} LV(s,j)x_{sj} + \rho\sum_{j=1}^{J}\sum_{r=1}^{R} w_{rj}z_{rj}$$

and the problem is to minimize $z(\rho)$, subject to constraints (1) and (2) and road network feasibility. The parameter, ρ, is used to drive the solution algorithm to produce a spectrum of solutions with differing proportions of road cost to lost volume. After solving the model for a range of values of ρ, we have the range of solutions to produce the trade off curves.

METHOD OF SOLUTION

We have chosen to use a Tabu Search strategy to solve this problem. Tabu Search (TS) belongs to the *metaheuristic-heuristic* class of algorithms, where local optimization (local neighborhood search) is enhanced with strategies which enable the search process to go beyond local minima. The seminal ideas behind tabu search were first developed by Fred Glover (Glover 1986), and independently by Pierre Hansen (Hansen 1986). Tabu search is a history-based or memory-based strategy; information from previous phases of the search is used to direct future phases. We refer the reader to (Glover 1992) for a complete description of the TS method and applications, and to (Richards 1997) for a complete description of the algorithms used in this work. Here, we will restrict the description to an overview of some of the technical aspects of solving this problem using TS. The following is an outline of the algorithm.

Tabu Search Algorithm

1. Generate a feasible starting solution x using Monte Carlo methods, and calculate the road network.
2. Neighborhood search: Evaluate each non-null move $x_s \leftarrow j, j \in [1, J+1]$ using the evaluation function $z'(x,\rho) = LV + \rho RC + \alpha Dev\_total + \beta Dev\_per + \gamma Dev\_\max open$, where LV is the total loss penalty, RC the road cost and terms Dev_total, Dev_per, Dev_maxopen are penalty terms for infeasible moves. The coefficients α, β, and γ are dynamically assigned throughout the search process to effect a strategic oscillation through the boundaries of the feasible region (Glover 1992, Gendreau *et al.* 1991).
3. Accept the best non-Tabu move, implement the move and update the Tabu List Structures
4. If $z(\rho)=z'(\rho)$ (i.e., the solution is feasible) is less than any found so far, save the solution.
5. If the stopping rule is met, stop.
6. If diversification is required, execute diversification routine.
7. Go to neighborhood search.

Some comments on the technical aspects of neighborhood search and move implementation are in order. For each move evaluation or implementation we do a depth first graph search (Sedgewick 1983, Lockwood and Moore 1992) to calculate opening sizes and any ensuing violations of the adjacency constraints. Stand assignments

induce a road network design problem which is solved using a path heuristic. Since this problem ***RNP(x)*** is *NP-hard,* we use a heuristic procedure to solve this problem. The heuristic is based on a modification of Prim's Shortest Path Spanning tree algorithm (Sedgewick 1983). This algorithm is fully described in (Richards 1997). Tabu tenure and the requirement for diversification is determined by a reactive mechanism which measures cycling of the search trajectory (Battiti and Tecchioli 1995). See (Richards 1997) for further details of the tabu search method.

EMPIRICAL RESULTS

We tested the method on an area of 1,039 stands, with a proposed road network of 125 links. The total harvest target over four 5-year planning periods was 2 million solid cubic feet, equally distributed between periods. Total percentage deviation allowed was 2 percent, periodic 5 percent. In this region, the maximum opening size is 125 acres and adjacency delay 10 years. The cost to build 1 km of road is $5,000 and is discounted at 10 percent per year.

Solutions

Figures 6 and 7 show solutions for ρ equal to 1.0 and 10.0. Figure 8 summarizes the number of kilometers of road to be built in each period. Figure 9 shows that it is possible to construct feasible solutions harvesting stands which are accessed by the existing main roads. The cost in lost productivity is, however, extremely high, approximately 1 million cubic feet of lost volume.

Trade Off Curves

The trade off curve is the efficiency frontier for the two attributes, minimum road cost and minimum lost productivity. Figure 10 shows the curve produced from this dataset. At the extremes, we see that it "costs" 950,000 cubic feet of lost volume to spend nothing on road building. At the other extreme, we can spend $175,000 on road building (at $5,000 per km) to drive the lost volume to approximately 300,000. More importantly, we can see that by increasing investment in road building to $40,000, we can reduce the lost volume to approximately 425,000 cu. ft., a reduction of 50 percent. Furthermore, the curve shows us that there is very little point in increasing road spending to more than $80,000 since the returns on reducing lost volume are small.

DISCUSSION AND CONCLUSIONS

We have presented a model and a workable solution method to perform trade off analysis in the context of tactical forest planning. We believe that the trade off analysis provides valuable information to decision-makers and should improve the planning process. We

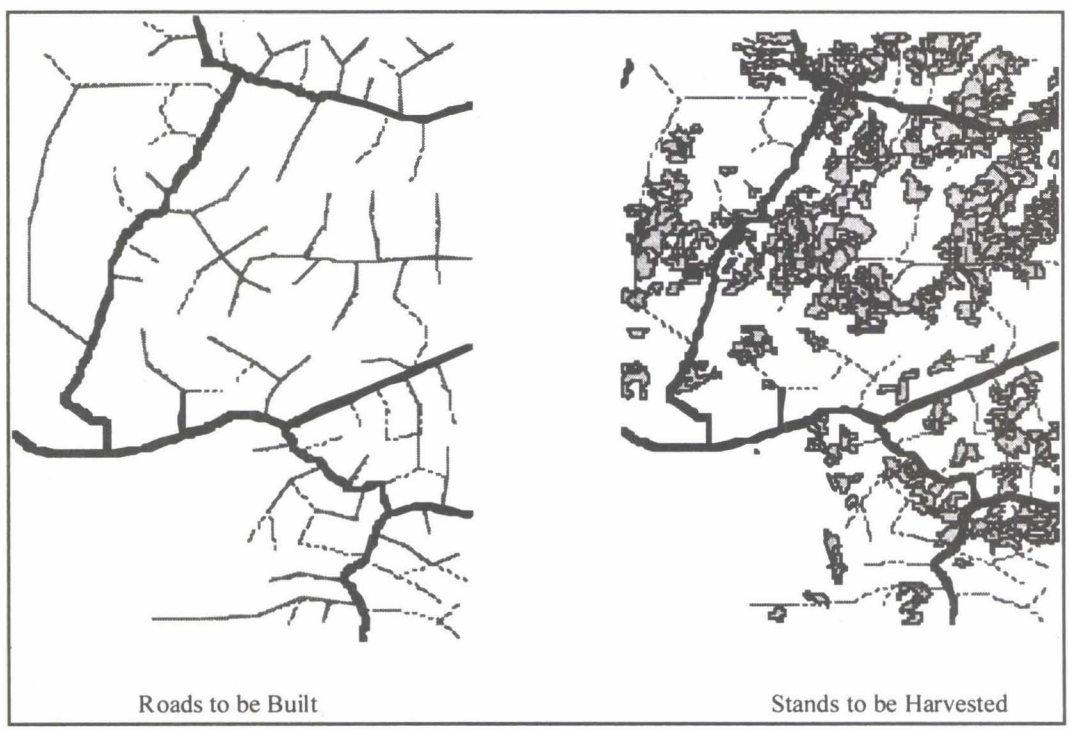

Figure 6.— Solution for ρ = 1.0. Solid lines show roads to be built; dashed lines the unbuilt links and heavy lines the existing main roads. Roading Cost is $99,132 and lost volume penalty 306,526 cu. ft.

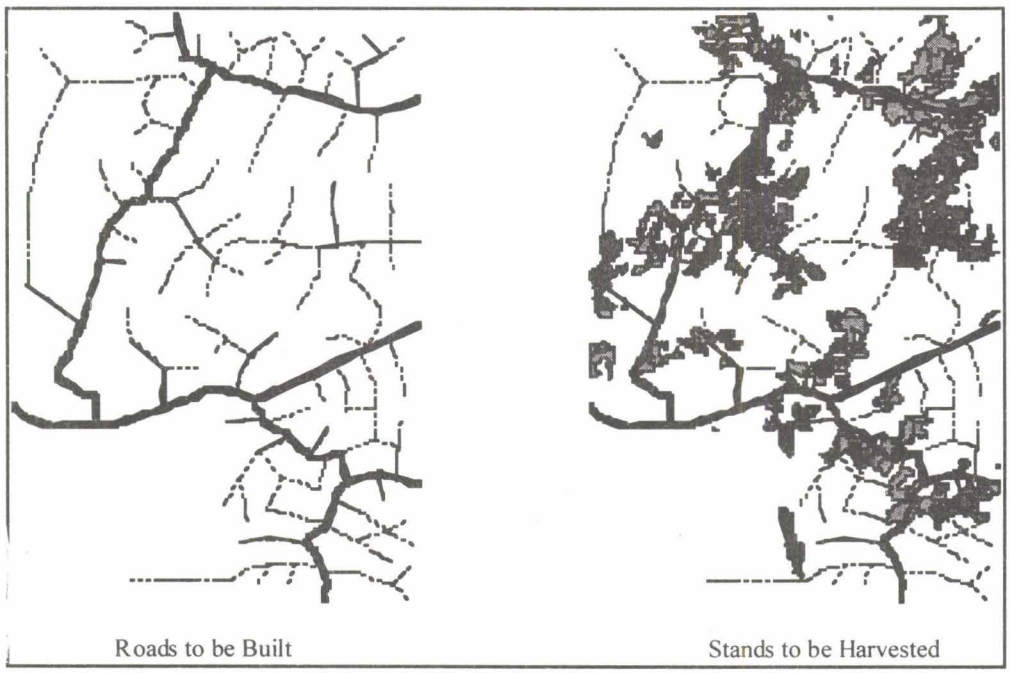

Figure 7.—*Solution for ρ = 10.0. Roading cost is $24,840 and lost volume 563,444 cu. ft.*

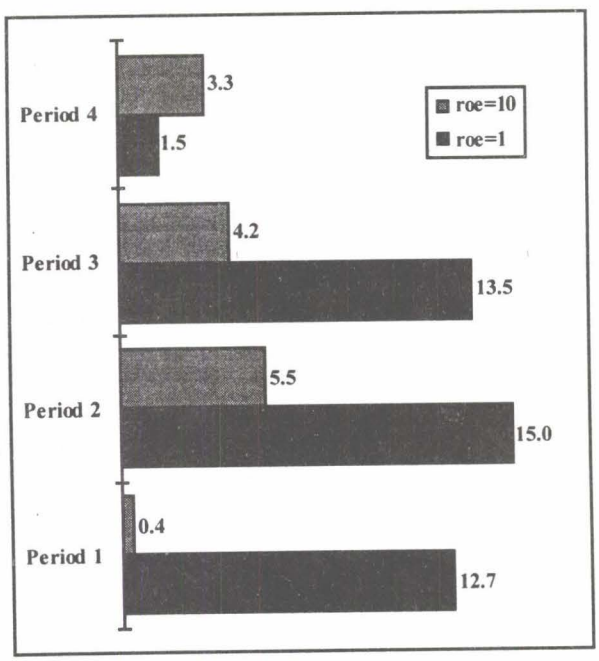

Figure 8.—*Km of roads built by period.*

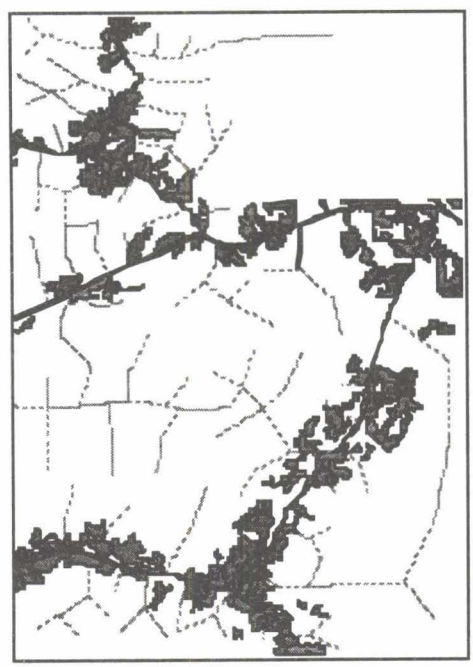

Figure 9.—*Solution for ρ = 20.0 No roads.*

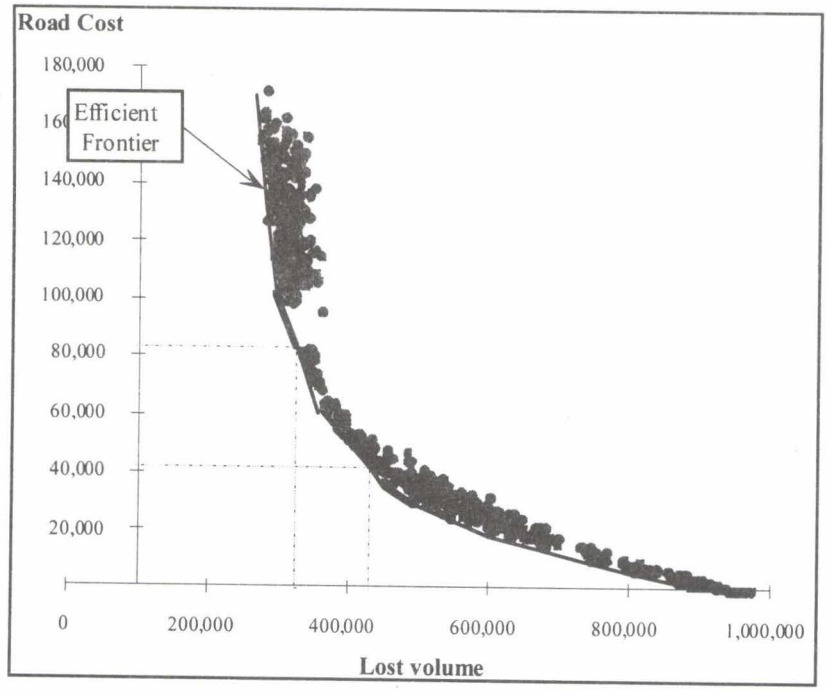

Figure 10.—*Trade off curve.*

have also produced a Tabu Search algorithm which is applicable to this problem. Our modeling of adjacency delay and maximum opening size restriction using graphs and multiperiod openings does not require pre-blocking of stands, and does not require the planning period length to be equal to the green-up period. The graph search calculations are practicable in sparse forest adjacency graphs. In our model, we have considered only adjacency and production constraints. The method does not preclude the inclusion of other constraints, although some work would be necessary to refine the neighborhood search and diversification strategies in the Tabu Search algorithm.

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LIQUIDITY CONSTRAINTS AND COLLABORATION IN TIMBER SELLING

Jussi Uusivuori[1]

ABSTRACT.—The effects of liquidity constraints on the profitability of forest management plans, and the potentials of a collaborative timber selling scheme to counteract these effects are examined. It is shown how forest owners can increase the profitability of their forest assets by pooling them. Collaborative timber selling scheme offers a way to reduce the negative impacts of the capital-market imperfections by permitting the land owners, under certain conditions, to partially restore the separability of consumption and timber production decisions. Pooling forest assets enables the landowners to better take advantage of their price expectations, and increase the expected value of their forest holdings. Specifically, interpretable measures for two-owner collaborative benefits are derived in the case where the forest owners face borrowing constraints. These benefits are shown to directly depend on the expected timber price changes, interest rates and the extent of borrowing constraints. The prospects of being able, through the collaborative scheme, to circumvent capital market imperfections, translate into the possibility of reducing welfare losses due to those imperfections.

INTRODUCTION

Capital market imperfections and liquidity constraints can be argued to result in a distorted distribution of resources in the economy between present time and future. In the case of forestry, as the privately optimal forest assets or timber stocks are kept below their socially optimal long-term levels, the capital market imperfections lead to sub-optimal timber supplies. This, in turn, results in welfare losses of the forest owners and of the entire society. In practice, it is usually the small non-industrial private forest owners who face capital market imperfections.

This paper examines capital market imperfections and their effects on the values of forest assets and presents a possible remedy to counteract the negative effects of capital market imperfections and liquidity constraints. The main question this paper attempts to answer is: how could private forest landowners collaborate in timber selling to increase the profitability of their forest-assets. The paper shows how a straightforward theoretical outcome from a constrained resource-management problem has some clear-cut and strong practical implications, and readily lends itself to forestry applications.

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More specifically, the question examined is what the economic conditions are in which collaboration yield benefits to forest owners. The study finds that when there are imperfections in the capital markets, liquidity constrained forest owners gain benefits through collaboration.

First, in this paper, a two-period profit maximization problem of liquidity constrained consumers endowed with forest assets and an access to capital markets is presented. Next, the effects of a simple collaborative scheme on the constraint structure of a combined model is demonstrated. Then, interpretable measures for the benefits of the collaboration are derived, and finally, some practical aspects of the modeling implications are discussed.

THE MODEL

Next, the idea of collaborative pooling of forest assets is demonstrated within a profit-maximizing model framework. The basic set-up of collaborative pooling of forest assets is simple. Two forest owners with compatible price expectations and differing types of forest holdings (in terms of timber assortments) can jointly utilize one of the two types of forests first to meet their liquidity needs of today, and leave the other forest site with higher price and value prospects unused till tomorrow. Since more of the forest with better economic outlook can be saved till tomorrow than by acting alone, the collaboration increases the expected combined proceeds of the two forest assets. Therefore,

also, the collaboration scheme offers natural incentive to both of the forest owners to collaborate.

A forest owner seeks to organize his forest-asset management plans so as to maximize an inter-temporal profit function. We study the maximized values of two forests in two different managerial regimes, first when two forest owners are acting independently, and second, when they plan timber selling in collaboration with each other.

In the case of the two forest owners acting independently, the combined constrained maximized value of two forest assets (i = 1,2 to denote the two forest assets and the two forest owners) can be expressed as follows:

$$(1)\quad V_t^{1,2}(a^i) = \underset{a^i}{\text{Max}}\ \{\Sigma_i p^i_t a^i Q^i_t + (1+\delta)^{-1} \Sigma_i E(p^{*i}_{t+1})(1+F^i)(1-a^i)Q^i_t - rB^i)\}$$

$$\text{subject to } p^i_t a^i Q^i_t + B^i = C^i_t \text{ for } i = 1,2.$$

In the above, the symbol denotations are the following:

$V_t^{1,2}(a^i)$	Discounted expected value of two independent forest assets combined
Σ_i	Summation over i = 1,2
p^i_t	Price at period t of timber assortment contained in forest holding i
a^i	Share of period t timber cuttings of the total timber in the forest holding, ($0<a^i<1$), forest owners acting independently
Q^i_t	Timber volume in forest holding at t
B^i	Upper bound on the amount of borrowing for forest owner with assets i
δ	Time preference factor, common for both forest owners
E	Expectation operator
p^{*i}_{t+1}	Timber price at period t+1, a random variable
F^i	A concave (in Q) growth function
r	Interest rate
C^i_t	Consumption at period t

In the model, the forest owners are assumed to be credit rationed and to have only limited access to capital markets, with the upper bound of B^i as the amount of borrowing which they cannot individually exceed. The decision variable is a^i, the percentage that the forest owner wants to cut at the first period of the total volume of his forest assets. The rest, given by the percentage $1-a^i$, is left to the second period. The expected value of this remaining forest, $Ep^{*i}_{t+1}(1+F^i)(1-a^i)Q^i_t$, depends on the unit timber price on the second period and on the growth of the forest.

The a^i are chosen so that $(1+r)/(1+\pi^i) < (1+F'^i)$, where π^i are the expected change rates of timber prices, $(Ep^{*i}_{t+1} - p^i_t)/p^i_t$, and F'^i are the first derivative of the growth function at the levels $(1-a^i)Q^i_t$. This implies, given the concavity of the growth function, that the credit rationed forest owners cut more in the current period than what is socially optimal. Thus capital market imperfections distort the optimal allocation of resources between financial and forest assets. This and the timber supply implications of credit rationing are well documented in Koskela (1989) and in Kuuluvainen (1990).

In the case of the two forest owners acting in collaboration, the combined constrained maximized value of two forest assets can be expressed as follows:

$$(2)\ V_t^{1,2}(a^i) = \underset{\alpha}{\text{Max}}\ \{\Sigma_i p^i_t \alpha^i Q^i_t + (1+\delta)^{-1}\Sigma_i E(p^{*i}_{t+1})(1+F^i)(1-\alpha^i)Q^i_t - rB^i)\}$$

$$\text{subject to } \Sigma_i(p^i_t a^i Q^i_t + B^i) = \Sigma_i C^i_t$$

In (2) α^i are the shares of the two forest assets cut in the first period when the two forest owners are collaborating with each other. They are thus the collaborative decision variables, chosen from the pool of the two forest holdings. For example, α^1 is the share of timber contained in the holdings of forest owner 1 which is cut in the first period, in order to maximize the expected value of the forest asset pool while satisfying the liquidity needs of the two forest owners. Comparing (1) with (2) it can be observed that the constraint structure in (1) places a stronger restriction on the management plans of the two forests than the constraint structure in (2). Therefore, the collaborative timber cutting management, described in (2) and defined by α^i, provides at least as high expected value of the combined forest assets as the individual timber cutting management defined by a^i in (1). We can write the following expression:

$$(3)\quad V_t^{1,2}(\alpha^i \geq V_t^{1,2}(a^i)$$

Next the question of what are the specific conditions in which the collaboration provides higher proceeds than the individual timber selling, is studied more closely. Also interpretable measures are derived for the collaborative benefits.

COLLABORATIVE BENEFITS

In what follows, the simplifying assumption of a linear growth function will be adopted. This enables one to proceed to easily interpretable measures of collaboration by working with boundary-point solutions. For a further illustration of the simplifying effects of a linear growth function under future price uncertainty, see Koskela and Ollikainen (1998). The linearity of the growth function implies that the growth of the forest is exogenously given to the forest owner.

With the linearity assumption, the expected discounted change rates of the unit values of the two forest assets can be expressed as:

$$(4) \quad D^i = (Ep^{*i}_{t+1}\,(1+q^i)(1+\delta)^{-1} - p^i_t)/\,p^i_t,$$

where q^i is the linear growth factor. Throughout the rest of the analysis it is assumed, without loss of generality, that $D^1 > D^2$, i.e., forest owner 1 is designated to be the one whose asset value is expected to rise more than the asset value of owner 2.

To tract down the optimal managerial choices of the forest owners, we need to establish an ordering of the expected returns of the two broad types of assets involved, the financial ones on the capital markets, and the forest assets on the timber markets. For this, we first presume the following configuration between the change rates (time-preference adjusted) of the assets: $D^1 > r(1+\delta)^{-1} > D^2$. The asset value of the first forest owner is expected to grow faster, whereas the asset value of the second forest owner is expected to grow slower than the prevailing interest rate on the capital markets. Under these conditions, the case of the forest owners acting alone is studied first, followed by the case where they act in collaboration with each other.

For the first forest owner it is now optimal to use up the entire personal borrowing quota, B^1, to cover as much as possible of the first period liquidity need through a loan from the capital markets, and only cover the rest of the liquidity requirement, $C^1 - B^1$, by selling timber. This way he saves as much as possible of his forest assets, which he expects to give a higher return than assets are gaining on the capital markets. Then the expected value of his forest assets under the liquidity constraint is given by:

$$(5) \quad V^1(a^1) = p^1_t a^1 Q^1_t + (1+\delta)^{-1}\,(Ep^{*1}_{t+1}(1+q^1)(1-a^1)Q^1_t - rB^1)$$

$$\text{with } a^1 = (C^1 - B^1)/\,p^1_t Q^1_t$$

According to (5) the asset value of the first forest owner is given by the first period timber selling proceeds plus the expected value of the remaining forest assets minus the interest payment on the first period loan due on the second period. As long as the liquidity constraint is binding so that $C^1 > B^1$, a^1 will be larger than 0, and some of the timber will be cut in the first period. If the constraint is not binding, $C^1 < B^1$, none of the timber is cut in the first period. It should also be noted that, since a^i's take values between 0 and 1, the liquidity constraint is assumed not to exceed the present value of the forest assets.

For forest owner 2 whose forest assets are expected to give a return lower than the interest rate, $(r(1+\delta)^{-1} > D^2)$, the optimal behavior is simply to sell the entire forest inventory in the first period and lend out the amount beyond the liquidity need, at interest rate r. The (expected) value of his forest assets therefore is:

$$(6) \quad V^2(a^2) = p^2_t a^2 Q^2_t + (1+\delta)^{-1}\,(p^2_t a^2 Q^2_t - C^2)r$$

$$\text{with } a^2 = 1$$

As long as $p^2_t Q^2_t > C^2$, forest owner 2 is not acting as a borrower on the capital markets, and is hence not bound by the upper limit of the borrowing constraint.

Next, the expressions in (5) and (6) can be summed, to obtain the expected combined value of the two forest assets in the case where the two forest owners are acting separately. After some manipulations we get:

$$(7) \quad V^{1,2}(a^i) = p^2_t Q^2_t + (1+\delta)^{-1}\,(Ep^{*1}_{t+1}(1+q^1)Q^1_t - r^*C^1 + (p^2_t a^2 Q^2_t - C^2)r)$$

In the above, r* can be called the 'virtual interest rate' and is expressed as follows:

$$(8) \quad r^* = r(1+\delta)^{-1} + (D^1 - r(1+\delta)^{-1})\,(1 - B^1/C^1)$$

In (7) the virtual interest rate r* defines the unit price of the 'credit' forest owner 1 needs to have to satisfy his first period consumption C^1. This credit is a combination of a loan from the capital markets and proceeds from timber selling. The timber selling amounts to 'borrowing' from the forest owner's own forest assets, since for the amount $C^1 - B^1$, he is refrained from receiving the expected rate of the value growth D^1 as a result of the borrowing constraint. It is important to note that the virtual interest rate r* is larger than the actual (time-preference adjusted) interest rate r:

$$(9) \quad r^* > r(1+\delta)^{-1}$$

Expression (9) holds because in (8) $D^1 > r(1+\delta)^{-1}$ and $B^1 < C^1$. The concept of virtual interest rate has previously been studied within forestry context by Kuuluvainen (1990).

Next we proceed to obtaining an expression for the expected combined forest asset value in the case where the two forest owners choose to collaborate with each other. This expression can then be compared with (7).

When collaborating with each other and pooling their forests the two liquidity constrained forest owners have more flexibility to manage their forests than when acting

alone. We want to know what is the optimal selling scheme under collaborative timber management, i.e., what are the α^i's in this case when $D^1 > r(1+\delta)^{-1} > D^2$.

When acting together, it is optimal for the forest owners to save till the second period the entire forest assets owned by forest owner 1, and generate the expected total value worth of $(1+\delta)^{-1} Ep^*{}^1_{t+1}(1+q^1)Q^1_t$. Furthermore, when acting together, the forest owners want to have the entire forest assets owned by forest owner 2 cut in the first period, and earn the selling income of $p^2_t Q^2_t$, plus the interest income on the amount exceeding the combined liquidity needs, $(p^2_t Q^2_t - C^1 - C^2)r$. Therefore $\alpha^1 = 0$, and $\alpha^2 = 1$. Then the combined expected asset value is given by:

$$(10) \quad V^{1,2}(\alpha^i) = p^2_t Q^2_t + (1+\delta)^{-1} (Ep^*{}^1_{t+1}(1+q^1)Q^1_t + (p^2_t Q^2_t - C^1 - C^2)r)$$

The term $p^2_t Q^2_t - C^1 - C^2$ can either be positive or negative, or zero. If the income from selling the forest assets 2 exceeds the combined consumption requirements, the remaining money can be lent out on the capital markets at interest rate r, while if the converse is true, the remaining consumption needs can be satisfied by borrowing from capital markets at the same rate. (We assume that $p^2_t Q^2_t - C^2 \geq C^1 - B^1$, i.e., the second forest owner's forest assets, net of his own consumption, are at least as high in value as the first forest owner's consumption subtracted by his borrowing limit.)

By comparing the two expressions (7) and (10) of the expected values of the combined forest assets in the two alternative schemes above, it is easy to see that $V^{1,2}(\alpha^i) > V^{1,2}(a^i)$. This result comes out from the fact that the virtual interest rate for forest owner 1 is higher than the market interest rate, as stated in (9). Therefore, collaboration in timber selling promises higher returns for the forest owners than acting independently from each other. Through collaboration, the consumption of forest owner 1 can be satisfied based on 'borrowing' either from the capital market or from the forest assets of the second forest owner, which both credit sources are less costly than the forest assets of the first forest owner, since $D^1 > r(1+\delta)^{-1} > D^2$. Thus, collaborative selling leads to expected gains over individual selling, since it offers a means to partially circumvent the liquidity constraints imposed on the forest owners.

Subtracting (7) from (10), the economic gains from collaboration can be expressed as follows:

$$(11) \quad (D^1 - r(1+\delta)^{-1}) (C^1 - B^1)$$

The benefits of pooling forest assets and integrating timber selling are expressible as the difference of the expected percentage returns of the forest assets with the better price outlook, and the actual interest rate, $D^1 - r(1+\delta)^{-1}$, times the difference between the consumption expenses and borrowing constraint of the owner of these forest assets, $C^1 - B^1$.

Above the case has been analyzed when $D^1 > r(1+\delta)^{-1} > D^2$. The two other cases of configurations (recalling that we set $D^1 > D^2$) between timber price expectations and the interest rate, $D^1 > D^2 > r(1+\delta)^{-1}$, and $r(1+\delta)^{-1} > D^1 > D^2$, can be studied in a similar way. Accordingly, one finds that the collaborative benefits in the former case will be:

$$(12) \quad (D^1 - D^2) (C^1 - B^1)$$

Now the expected benefits from collaboration are determined by the difference in the expected returns of the two forest assets, and the extent of the borrowing constraint of the forest owner with the forest assets of the higher price outlook. On the other hand, when $r(1+\delta)^{-1} > D^1 > D^2$, i.e., the interest rate is higher than either one of the expected returns of the two forest assets, both forest owners are cutting their entire timber stocks in the first period in the case of individual selling, as well as in the case of collaborative selling. Therefore, no benefits could be gained through collaboration.

DISCUSSION

The above analysis has demonstrated how, through a collaborative timber selling scheme, liquidity constrained forest owners can achieve gains in the expected values of their forest assets. Pooling their forest resources, two forest owners can partially circumvent borrowing constraints imposed on them individually on the capital markets. Recently, some empirical evidence has been found suggesting that non-industrial private forest owners may be subject to (perceived) credit rationing (Kuuluvainen and Salo 1990, Kuuluvainen *et al.* 1996).

The reasons for the existence of credit rationing among forest owners—or other asset holders—could lie on the fact that creditors and debtors have asymmetric information, or simply on creditors' risk management policies. It seems plausible to assume that it is mainly the small landowners that might face borrowing limits. Therefore, the collaboration in timber selling could offer a possible means specifically for these forest owners to lessen the effects of credit rationing, and improve the profitability of their forest management operations.

In this study, some simplifying assumptions were used to make the collaborative benefits more interpretable. These benefits were shown to depend on the differences between the expected asset growth rates on the capital and timber markets, and on the extent of the credit rationing. The higher the expected change in the value of

the forest assets of one of the forest owners compared to the interest rate, and the tighter the credit rationing, the larger the benefits of the collaborative scheme will be.

In a further analysis, it could be shown, that not only does the collaboration in timber selling lead to improved profitability under the conditions of credit rationing, but also, when the capital markets exhibit imperfections in general—in the sense of differing borrowing and lending rates of interest - the same type of forest asset pooling offers a means to avoid the negative effects of these imperfections. This analysis, however, is left out of this report.

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PROJECTING FUTURE DEVELOPMENT OF THE RUSSIAN FOREST SECTOR USING FOREST SECTOR MODEL

A. Moiseyev[1]

ABSTRACT.—The Russian forest sector is currently under pressure of an economic crisis. Average annual production of the roundwood has decreased about 3 times since 1989. Limited domestic demand for forest products restricts production growth and the development of the technology in forest industries. At the same time forest resources are not fully utilized. However, this situation may change in the future. The key factor affecting the future of the forest sector is annual GDP growth. The PELPS III model is utilized for projecting the future of the Russian forest sector. Preliminary results show that it will take a long time to restore past production levels in the forest industries. This paper also outlines the future development of a forest sector model using a partial equilibrium framework for forest industries and forestry sector.

INTRODUCTION

Russia is a huge country with great forest resources and high potential for the forest sector within the national economy. However, the Russian economy is experiencing very heavy and long crises. Production of the forest sector decreased from 2 to 3 times. Potential of the Russian forest is utilized only on 1/3. The Russian federal programme of forest sector development (ROSLESPROM 1995) is planning to increase production of the forest industries more than 2 times by 2005. However, there is no scientific analysis behind this programme. It looks nice, but maybe not realistic. Nevertheless, even that will not put Russian forest sector in the position it was before 1990.

MAIN RUSSIAN FOREST SECTOR CHARACTERISTICS

Forestry Characteristics

Russian total forest land area is 1,110,481.6 thousand ha, from which 705,789.2 thousand ha (73,028 million m^3) are forested lands, including 507,708.2 thousand ha of coniferous forests. Average annual growth is 822 million m^3. Only 351,095.9 thousand ha (43,467 million m^3) of forests are exploitable. Distribution of exploitable forested lands among European and Asian parts of Russia are shown in table 1. Most forested lands are in the Asian part. However most of the unexploitable forests are in the Asian part as well. European forests present the most productive forests (annual increment is almost twice as high as that in the Asian part of Russia).

Table 1.—*Distribution of exploitable forested lands in Russia, 1993*

Region	Total forested lands	Exploitable forested lands	Ratio of exploitable to total forested lands	Annual increment
	---------- *Percent* ----------			*CUM/ha*
Russia	100.00	100.00	61.80	1.34
European Russia	20.90	30.10	88.90	2.00
Asian Russia	70.10	67.90	54.60	1.10

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Annual allowable cut (AAC) is 529,407 thousand m^3 in 1993. However, it was utilized only at 1/3 in 1993. Table 2 gives an historical retrospective for actual use of AAC in Russia in different time periods. There were periods in the past when coniferous forests were overcut. For coniferous forests in European Russia utilization of AAC was 59.2 percent in 1993. There are some regions in European Russia where this percentage is about 100 percent even now.

Forest Industry Characteristics

Forest industries in Russia were experiencing long crisis since 1990. Total removals, roundwood, and saw logs decreased almost 3 times from 1989 to 1995. However, in the pulp and paper industry the decrease is only 2 times (table 3).

In spite of the heavy crisis on the domestic forest products markets, export of roundwood, pulp and paper increased in 1995 in comparison with 1985 (table 4). However, Russia is losing external markets for sawn wood.

Table 2.—*Annual allowable cut in millions cubic meters and it actual use*

Annual allowable cut by years		Russia		European Russia		Asian Russia	
Years		Total	Conifer	Total	Conifer	Total	Conifer
1972	AAC	600.9	383.8	236.9	133.7	364.0	250.1
	Actual use, %	55.5	67.5	88.5	110.4	34.0	44.2
1987	AAC	615.0	389.8	229.0	124.9	386.0	264.9
	Actual use, %	52.0	59.5	79.0	90.9	35.9	44.7
1991	AAC	602.4	381.6	220.4	121.1	382.0	260.5
	Actual use, %	47.0	53.5	71.5	79.5	32.9	41.5
1993	AAC	529.4	319.1	197.8	99.6	331.6	219.5
	Actual use, %	32.9	37.7	51.4	59.2	21.9	28.0

Table 3.—*Production of roundwood and forest industry products in Russia from 1985 to 1995*

Product		1985	1989	1990	1994	1995
Total removals	10^6 m^3	337.3	338.4	303.8	118.9	114.6
Roundwood	10^6 m^3	237.7	247.3	221.4	79.8	80.8
Saw logs	10^6 m^3	142.2	144.9	129.2	52.7	47.5
Pulpwood	10^6 m^3	51.5	53.1	48.6	20.2	26
Sawn wood	10^6 m^3	79.6	81.9	75	30.7	26.7
Plywood	10^6 m^3	1.6	1.7	1.6	0.89	0.93
Particle board	10^6 m^3	4.67	5.65	5.57	2.63	2.21
Pulp	10^6 ton	7.95	8.11	7.53	3.31	4.12
Paper	10^6 ton	5.03	5.34	5.24	2.22	2.77
Newsprint	10^6 ton	1.57	1.72	1.72	1.04	1.46

Table 4.—*Export of roundwood and forest products from Russia*

Product		1980	1985	1990	1994	1995
Roundwood	10^6 m^3	16.93	15.43	15.00	13.50	18.00
Sawn wood	10^6 m^3	7.13	7.63	7.10	5.40	4.20
Plywood	10^6 m^3	0.31	0.41	0.32	0.59	0.66
Particle board	10^6 m^3	0.33	0.30	0.12	0.02	0.02
Pulp	10^6 m^3	0.82	0.97	0.39	0.94	1.30
Paper and board	10^6 m^3	1.02	1.10	0.89	1.05	1.45

Most of the Russian Forest Industry enterprises were privatized during 1991-1993. Majority of enterprises are now joint-stock companies. However, it does not make any real sense. The main problem for companies is very limited domestic demand for forest products due to the crisis of the Russian economy. Most of the forest companies are unprofitable. Nevertheless, the situation is different for different forest industry bunches. The best situation is in the pulp and paper industry (table 5). Domestic prices for paper are on the same level with international market prices. Pulp and paper companies are rather big and they act like monopolies on local wood markets. They dictate low prices for roundwood. As a result, harvesting is unprofitable. The sawmilling industry is not too monopolized. That is why it has very moderate profit.

There is one exclusion in all of the tables for profitability. That is the Far East Region. Apart from all other regions, pulp and paper industry and woodworking industry are unprofitable in Far East due to high production costs for everything. Nevertheless, the highest prices for saw logs on Japanese market make saw log export profitable. Almost all saw logs are exported from Far East to Japan and others Pacific Rim Markets. Any forest industry company excluding those dealing with roundwood export is unprofitable and are not working now in Far East.

DEMAND AND SUPPLY ANALYSIS FOR THE RUSSIAN FOREST SECTOR

Demand/Supply of Roundwood

Traditionally, wood supply forecast is produced by special state forest management organization (Lesproekt) for local forest management unit (Leshoz) once every 10 years providing forest inventory and forest management plans with enormous details including volume of intermediate and final cuts and allocation of all cutting activity as well as silviculture and thinning activity. Nevertheless, there is no analyses as to the basis of this type of forest management planning. It is based on the personal experience of a forester. No one is doing forest management planning on a larger scale and on the national level. There are no forest management models applied for the wood supply forecast at the national level. However, there are a number of approaches developed in the former Soviet Union for long term forest management planning dealing with wood supply. One of them (Komkov and Moiseev 1987) is focusing on maximizing sustainable cutting level. This model was applied to several regions in Russia in the late 1980's. Most of the models being developed in former Soviet Union times were optimization models. There is no econometric model applied to wood supply in Russia.

Demand/Supply Analysis of Forest Industry Products

Econometrics models are not used for demand/supply studies. Expert estimations were used for long and middle term forecasts in the forest sector on the country level. Nevertheless, there are some forest sector models applied on the regional level in the former USSR. One of them was developed in VNIPIEILesprom. This model is not partial equilibrium forest sector model. The model is minimizing total production and investment costs in the forest sector of KOMI republic starting from harvesting and finishing in various forest industries enterprises existing and planning. The model is dealing with a very high level of technical details, various timber products assortments. Demand for certain forest products is exogenous in the model. However, there are some studies carried out by international organization.

Table 5.—*Prices and production costs for some forest products in Russia in 1995*

Region	Newsprint		Sawn wood coniferous		Saw logs coniferous	
	Price	Production costs	Price	Production costs	Price	Production costs
			US$/CUM			
North region	532.0	336.0	76.0	73.4	17.1	18.6
North-West			43.8	37.1	18.3	18.1
Central			42.1	36.1	15.6	16.3
Volga-Vyatka	455.0	318.0	48.9	39.1	16.9	17.6
Central-Chernozem			50.0	46.4		
Middle Volga			44.3	42.3	20.0	19.6
Norht Caucasus			68.7	65.7		
Ural	551.0	361.0	40.7	36.3	14.8	15.9
West-Siberian			42.1	42.6	12.4	15.3
East-Siberian	445.0	284.0	77.8	70.4	17.4	19.5
Far East	569.0	647.0	66.4	71.2	48.0	41.4

IIASA Russian Forest Sector Studies

Charles Backman (1995) presents information about forest resources, forest product production, consumption and export in Russia and four Russian regions. Basically this report is just a description of the current Russian forest sector state. There is no kind of model used in the analysis.

Nevertheless, CINTRAFOR Global Trade Model (CGTM) (Perez-Garcia and Backman 1995) was applied for scenario analysis of the Russian Forest Sector regarding harvesting capital constrain effect on developing roundwood consumption. There are only two regions in the model (Russian West and Russian East). There is an assumption behind the modeling, that harvesting capital will be decreasing 5 percent per year for a long time due to low demand. As a result, after 2000, harvesting capital constrain will become the most important factor affecting further forest industries development. Prices for roundwood and forest products are considered as relatively low in comparison with international prices for the entire modeling period (difference is slightly decreasing to 2010, but still very significant). That was evident during 1996 already, that Russia's rapidly increasing domestic prices for most of its' forest products, and relatively low prices for roundwood on the local wood markets are only due to very monopolized forest industries, keeping high prices for final products and low prices for input wood products. So, price forecast is not reasonable in the model. Low prices are not constrain for the Russian forest sector.

International Studies

A first world forest sector study was carried out by IIASA using Global Trade Model (GTM) (Kallio *et al.* 1987). USSR was one of the regions in the world forest sector study. However, most of the numbers were not taken from the real USSR forest sector (only quantities of forest products manufactured in the base period seem to be correct, but not prices and production costs).

A recent world forest sector study has been carried out by FAO (1997) using the PELPS-based forest sector model. It is difficult to say how reasonable the figures and forecasts are for Russia in this study, because the most critical input information is not shown in the FAO report (i.e., prices and production costs).

EFI's Russian Forest Sector Study

EFI is carrying Russian forest sector studies using the PELPS III (Zhang *et al.* 1993) forest sector model. Base data are for 1995. Quantity manufactured are presented for 10 final products, 3 intermediate (pulp grades), 4 different kinds of roundwood and chips, 3 production, and 3 domestic demand region (European part of Russia, Siberia, Far East). Model incorporates also 3 demand regions outside of Russia for modeling of forest product exports. Export regions are West Europe (all European countries, excluding Italy, Greece, Spain, which are included to the next export region), South (countries which are exporting Russian forest products through the Black Sea), Pacific Rim (Japan, South Korea, China and other importers of Russian forest products in South-East Asia). The model utilizes information about domestic prices, production costs, and production capacities delivered by VNIPIEILesprom from the Russian official statistics. Critical factors for the study is annual GDP growth. Depending on GDP growth used, the model projects future Russian forest sector development. However, price and income elasticities were not estimated statistically in the study. They were used from FAO 1996 provisional forest product outlook (FAO 1997) due to lack of reliable historical price data in Russia.

Four scenarios depending upon annual GDP growth are used for projecting future development of the Russian forest sector. First scenario is "Low" scenario with 2 percent of annual GDP growth; second - "Medium" scenario with 3 percent GDP growth; third - "High" scenario with 5 percent GDP growth; and fourth - "Very high" scenario with 7 percent GDP growth. However, for all scenarios, GDP growth for 1st and 2nd years is -10 percent because of ongoing decline in production of most products in the forest sector and other sectors of Russian economy in 1996 and possibly 1997. Zero percent GDP growth is considered for 1998. Starting from the 1999 GDP growth is increasing 1 percent per year until it reaches upper level for a particular scenario. Base period for all scenarios is 1995. Results of the model runs for different scenarios are shown in table 6.

Figures for other paper and pulp products show a similar tendency. In case of high scenario production will be restored to the level of 1989 in 2020 and very high scenario in 2015. So, production of most pulp and paper products failed twice during 5-6 years, and it will take 20-25 years to restore past production level in case of high Russian economy growth. Export of newsprint is growing similar to Russian domestic consumption. Two percent GDP growth was used for export demand regions. In case of low scenario, low level of domestic demand limits export of newsprint because of capacity limitation. Low domestic demand does not stimulate rapid capacity expansion. AAC is an upper limit for roundwood supply in the model. Only in the case of high and very high scenario AAC starts to limit pulpwood supply near 2015-2020 in the European part of Russia, although there is no limit for saw logs that time. In this case, part of saw logs supply could be used for producing pulp.

Table 6.—*Projection for the future newsprint consumption, export and production (thousands tones)*

Scenario		1995	1996	1997	1998	1999	2000	2005	2010	2015	2020
Low	Consumption	775	705	627	635	637	642	678	749	823	876
Medium		775	705	627	635	637	642	719	806	939	1046
High		775	705	627	635	637	642	762	953	1169	1515
Very High		775	705	627	635	637	642	790	1048	1527	2015
Low	Export	948	977	981	995	1012	1017	1077	1151	1258	1328
Medium		948	977	981	995	1012	1017	1158	1307	1517	1662
High		948	977	981	995	1012	1017	1215	1515	1879	2345
Very High		948	977	981	995	1012	1017	1243	1617	2228	2864
Low	Production	1722	1681	1608	1630	1648	1658	1755	1901	2081	2205
Medium		1722	1681	1608	1630	1648	1658	1878	2113	2457	2709
High		1722	1681	1608	1630	1648	1658	1977	2467	3048	3860
Very High		1722	1681	1608	1630	1648	1658	2033	2664	3756	4881

PROSPECTS FOR THE FUTURE FOREST SECTOR MODEL DEVELOPMENT

Several types of optimization models were applied in modeling the national and international forest sector. A dynamic linear programming (DLP) optimization model for the Finish forest sector (Kallio *et al.* 1986) covers all branches at the aggregated level including forestry and forest dynamics. Model optimizes a discounted over time sum of net income from forestry and forest industries. Prices for final products are given as exogenous. This is not an equilibrium model. The DLP model is pure optimization model. In the TSM model, Sedjo and Lyon (1990) applied optimal control theory for projecting world timber demand and supply for roundwood products. Forest industries are taken to account thorough demand for roundwood, and prices for roundwood are endogenous. So this is an equilibrium model applied to the forestry sector. There are no other models for forestry dealing with equilibrium prices. Most of them are optimization models with maximizing discounted net present value. For time periods longer than 10 years this is something like a theoretical exercise because with a real interest rate all profit in the far future is essentially valueless. Simulation models in forestry may provide more valuable information, but forestry optimization models linked to the final products from wood may also be used for analyzing and modeling real forest sector problems.

There are a few partial equilibrium optimization models for the forest sector. Among them are the PELPS III based NAPAP (Ince *et al.*1993) and GTM model. PELPS III and GTM models use mainly optimization techniques and part simulation techniques. The optimization part is used to maximize consumers and producers surplus for finding equilibrium prices for final forest products like sawn wood; plywood; different types of pulp, paper, and panel products. Simulation technics are used for updating production capacities, changes in demand and supply curves, etc. So only current time periods have to be optimized. The dynamics of the forest sector is treated by simulating changes between time periods.

Partial equilibrium models like GTM and PELPS III represent the most advanced approach in studying the international and national forest sector for today. Demand for final forest products and wood supply from forests is taken into account together with model for manufacturing intermediate and final products and model for transportation of forest products between international and domestic regions. There are some differences between the GTM and PELPS III model in modeling capacity expansion and changes of wood supply depending on the growth of forests. Wood supply in GTM model is shifted from t time period to $t+1$ through internal simple forest growth model. In PELPS III model it may be done manually through predefined changes in wood supply before actual model run or using external forest growth model linked to the PELPS III model (It was done using this way in the NAPAP PELPS-based model linked to ATLAS (Mills and Kincaid 1992) and TAMM model (Adams and Haynes 1995) for the projecting future development of the North American forest sector). However there are no options for modeling different forest management regimes in the GTM model. In PELPS III—base model may be provided by adequate forestry model. At the present time, wood supply in partial equilibrium models is modeled as a black box with quantity of wood supplied as dependent variable and price as a main independent variable. For the demand side, this is the only way to model particular demand—a black box. Production process may be modeled as a black box as well (it was done in TAMM model), but in PELPS-based models production of forest products is considered as simple input-output model using so-called activity analyses model. However, supply of wood from the forest is considered as black box using econometric equation for wood supply depending on price and three possible shifters. Activity analysis may

also be expanded to wood supply from the forest like it was done in TSM model. In this case, criteria of the optimization problem is the following:

$$(1)\quad Max \leftarrow Z = Z_d - Z_m - Z_c - Z_t - Z_h$$

where:
Z_d is an area under demand curves,
Z_m is a sum of a net manufacturing costs,
Z_c is a sum of a investment costs,
Z_t is a sum of a net transportation costs,
Z_h is a sum of a net harvesting and regeneration costs.

In a typical forest management planning model Z_m, Z_c, Z_t are not used and Z_d is considered as revenue from the sale of roundwood from the forest with constant prices. This may be true for a particular forest owner or a firm, but it's not true for a large-scale forest management plan on the national or regional level. This is because prices depend on the quantity of roundwood sold. In the DLP forest sector model similar optimization criteria may be applied but again with constant prices. However, equilibrium prices were applied by Kallio and Soismaa. (1986) in Stackelberg game using nonlinear optimization software for steady state analysis of the finish forest sector. The nonlinear optimization techniques limit the size of the study object. In the TSM model, consumer and producer surpluses are the maximization criteria consisting of Z_d and Z_h. In the case of competitive market:

$$(2)\quad Z_d = \int_0^{D^*} P(D)\,d\,D$$

where:
P(D) is price as function of forest product quantity consumed;
D^* is an equilibrium quantity.

In the case of monopoly:

$$(3)\quad Z_d = P(D) \times D.$$

Because of the Z_d the optimization problem is nonlinear. However PELPS III model uses stepwise linear approximation for Demand Curves. It allows more effective linear programming optimization techniques. There is another problem in the forestry sector modeling. In the case of using Z_h as a sum of harvesting and silviculture costs, it is necessary to specify constraints for sustainable (non-decreasing) wood harvest. Otherwise, model may simulate that most of the wood would be consumed in the initial state. The model would not produce any regeneration after final harvesting if not to apply some constraints for doing this with relation to harvesting activity. In most cases like the Finish forest sector DLP model, constraints for the final forest state is applied in order to ensure certain results of the model run. The final state is usually considered as an optimal steady state. For the forest, this state is very close to the so-called "normal" forest. For forest industries it means equilibrium prices and no production capacity expansion. Of course, this is a bit artificial state and it used to be a theoretical assumption. From the steady state point of view, we have to create an optimal future forest sector state, and then optimize movement of the system from current state to this future final state through a number of steps using one or more optimization criteria. However, determination of optimal final state is a rather difficult question because of very high uncertainty of the future, especially from an economic point of view. For the forest industries sector time period like 10-15 years would be more than enough. More long period projections would be insufficient because of high future uncertainty. However, this time period is not enough for forestry to ensure certain future forest state. On the satisfactory level, that may be done using age distribution of the forest lands in the initial state. The model for optimizing harvesting at the current time with taking into account sustainable wood harvesting in the future and different systems of silviculture activity was described by Komkov and Moiseev (1987) and Moiseyev (1989). Within this framework for forestry sub sector it becomes possible to combine partial equilibrium model for the forest industries like PELPS III with the forestry model. The LP model is used for maximizing allowable cut level subject to age classes distribution and within silviculture activity system or minimizing silviculture and harvesting expenses subject to certain volume of harvest and sustainability constraints. In the last case forestry model can be easily integrated with partial equilibrium forest industries model.

Below is a short description of this approach. Harvesting and regeneration costs from equation 1 is the following:

$$(4)\quad Z_h = \sum_k \sum_l C_{kl} \times \chi_{kl},$$

Subject to:

$$(5)\quad \sum_l x_{kl} \le \frac{1}{m+1} \sum_{m=0}^{M} \sum_l S_{km},\ M=0,1,2,...,M^*;\ k=1,2,...,K$$

where:
x_{kl} is the area harvested that is going to be regenerated using system *l* of silviculture activity on forest lands of type *k*;
c_{kl} is the corresponding harvesting and regeneration costs;
S_{km} is the area under forest land of type *k*, age class *m*;
M=0 is the mature age class; M=1 is the age class prior to the mature age class; M=M* is the youngest age class (this class includes area after clearcutting that will be afforested using system *l* of silviculture activity.

Every x_{kl} represents a particular system of silviculture activity in the forest lands of type *k*. This is equivalent to different production technologies in forest industries sector. Constrain 5 represent requirements for the future sustainable harvesting. In the integrated forest industries and forestry activity analysis model one more type of constraint should be presented linking the demand for a certain type of wood by the industry side to supply of this wood from the forestry side.

CONCLUSION

The main idea for further model development would be determination of the most important factors affecting demand and supply of forest products. The weak point of existing forest sector models is the very aggregated forestry sub model. There are usually no any options for modeling different forest management regimes. In most European countries forest management should be considered an important factor affecting to timber supply. On the other side, many forestry models can model different forest management regimes at a very detailed level. They can provide detail analyses for supply of wood. But they assume constant prices for wood in the current moment as well as in the future, and demand for wood is not taken into account. It is evident that there are certain interdependencies between demand for forest products and supply of wood from forests. Both demand and supply should be modeled at once on an acceptable level of detail.

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MODELING GLOBAL TIMBER TRENDS IN FOREST PRODUCTS PRODUCTION, CONSUMPTION AND TRADE

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ABSTRACT.—This model was developed to upgrade the FAO global forest products outlook projection system. Its purpose is to analyze and project world forest products consumption, production, and trade. The system deals with 182 individual countries, 3 classes of roundwood, sawn wood, three kinds of panels, three of pulp, waste paper, and three types of paper and paperboard. The system is built on market equilibrium theory, with imperfect foresight. The short-term equilibrium is modeled by price-endogenous linear programming determining production, consumption, trade, and market-clearing prices in any given year, subject to short-term capacities of production. Year to year changes are represented by equations predicting shifts in demand due to GDP growth, capacity expansion as a function of current profitability, and technical change. The forecasts are conditional on exogenous estimates of maximum timber supply in each country, up to 2010. Inertia constraints limit the short-term adjustment of trade in response to market forces. The applications of the system to the world forest sector are described.

INTRODUCTION

Forest products are vital commodities for the sustenance and growth of every country in the world. The FAO is responsible for producing long-term projections of future consumption, production and trade of forest products, by country. The objective of this study was to revamp and make operational the FAO global forest products outlook projection system.

The approach was to develop a dynamic spatial equilibrium model of the world forest sector. Then, the model was applied to project forest products consumption, production, and trade under the most likely scenario of economic growth and timber supply constraints. As in past FAO projections, the assumed rates of economic growth, measured by GDP are critical in determining final demand. A new feature is the constraints defining the timber supply potential of each country. The projected demand for final products in the world cannot exceed the global wood-growing potential, after allowing for trade in raw materials or finished products between countries. Depending on market conditions, less wood may be cut than can potentially be produced, but not more. Therefore, the assumptions regarding timber supply potential are also critical. Given the uncertainties surrounding these elements, three scenarios were simulated.

The first part of the paper introduces the methodology of the Global Outlook Study model of 1996 (GOS-96), describes the countries/regions and the products included in the model, and discusses the demand equations and the supply constraint assumptions. Part two summarizes projections for 1995 to 2010 of consumption, production and trade in the main regions of the world.

THE GLOBAL OUTLOOK MODEL (GOS-96)

The GOS-96 model, was developed with the Price Endogenous Linear Programming System (PELPS III) (Zhang *et al.* 1993). PELPS is a general modeling tool for sector analysis. It finds a spatial, competitive equilibrium by maximizing the sum of producer and consumer surplus subject to material balance and capacity constraints in each country, for each year. Because material

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flows throughout the system must balance, it helps check the consistency of data, and insures the coherence of projections.

In each projection year, for each country and commodity, supply (domestic production plus imports) is equal to demand (final consumption, plus input in other processes, plus exports). Demand for wood or intermediate products derives from the demand for final products through input-output coefficients that describe the technology in each country. The supply of raw wood in each country is constrained by the wood supply potential. The supply of recycled paper is constrained by the waste paper supply, which depends on paper consumption and recycling rates. Imports and exports are balanced, at world levels and in each country. And, the projected prices for each commodity are such that they clear markets: at those prices demands are equal to supplies in each country.

From one year to the next, demand changes in each country due to assumed changes in income. The wood supply potential changes according to the chosen scenario. Technology also changes, especially the amount of recycled fiber used in making paper and paperboard. Capacity increases or decreases according to new investments that depend on past production and the profitability of production in different countries, as revealed by the shadow price of capacity. Then, a new equilibrium is computed subject to the new demand and supply conditions, new technology, new capacity, and inertia constraints that limit the change in exports and imports from year to year. The general principle of the PELPS system is, then, that markets optimize the allocation of resources in the short run (within 1 year). Long-run resource allocation is partly governed by market forces, as in capacity expansion and trade, and also by other forces such as: the wood supply potential determined by forest policy, the waste paper recovery rates by environmental policy, the trade inertia that depend in part on international agreements, and the techniques of production determined by exogenous progress.

This system has been used to develop the North American pulp and paper model (NAPAP), the North American solid wood model (NASAW), and by the International Tropical Timber Organization (ITTO) to develop the Asia-Pacific Tropical Timber Trade model. The Asia-Pacific Forest Products Model of Zhang *et al.* 1996, is also based on the PELPS system. The GOS-96 model is a natural extension of past FAO methodology. The demand for forest products continues to depend critically on income. The additions are: a detailed description of supply linked to demand so that production and consumption projections are fully consistent, and, prices that clear markets, as they must in the real world. The mathematical formulation of the model is given below.

Hierarchical Structure

The GOS model has a hierarchical structure. It consists of one main model called WORLD, and one sub-model for each region: AFRICA, AMERICAS, ASIA/OCEANIA and EUROPE/FORMER USSR, each one solved with trade flows that are consistent with the WORLD model.

Each region of the WORLD model has: (1) demand (consumption) of fuel wood, other industrial roundwood, sawn wood, veneer and plywood, particle board, fiberboard, newsprint, printing and writing paper, and other paper and paperboard; and (2) production (supply) of fuel wood, industrial roundwood, other fiber pulp, waste paper, sawn wood, veneer and plywood, particle board, fiberboard, mechanical pulp, chemical pulp, newsprint, printing and writing paper, and other paper and paperboard. Also, each region imports from and exports to the "world market."

A similar structure applies to the regional sub-models. For example, in the AMERICAS sub-model, there are 35 countries, each with a demand and supply of the same products as in the WORLD model. Each country has imports from and exports to the "world market." However, the total imports and exports of all countries in, say, the AMERICAS are constrained to be equal to the total imports and exports of the AMERICAS in the WORLD model.

Countries and Products

The countries in each sub-model are those recognized in the FAO Yearbook of Forest Products. The AFRICA sub-model has 50 countries, the AMERICAS has 35, ASIA/OCEANIA has 50, and EUROPE/FORMER USSR has 45 countries. In addition to country detail, seven regions and two economic classes are used in reporting the results.

GOS has final demand equations for fuel wood and charcoal, other industrial roundwood, sawn wood, veneer sheets and plywood, particle board, fiberboard, newsprint, printing and writing paper, and other paper and paperboard. The supply equations for fuel wood and charcoal, industrial roundwood, and other fiber pulp are horizontal, up to the maximum sustainable production. Waste paper supply is constrained by the quantity of paper recovered, a function of paper consumption.

Demand

The demand equations of GOS-96 assume that national demand for forest products is determined by economic activity (GDP) and real prices. Let q_{it} (of price p_{it}) be the amount of a forest product consumed or imported by a country i during year t; with i_{it} an index of the price of all other goods and services used in combination with this product to produce an output designated by the variable y_{it}, here the real gross domestic product. Then, assuming cost minimization under a Cobb-Douglas technology with constant returns to scale, coupled with a partial adjustment of actual towards desired consumption, leads to the following derived demand (Chou and Buongiorno 1984, Baudin and Lundberg 1987):

$$\ln(q_{it}) = \alpha_i + \beta \ln(\frac{p_{it}}{i_{it}}) + \gamma \ln(y_{it}) + \delta \ln(q_{it-1}) + u_{it}$$

For estimation, all countries in the world were divided into high, medium, and low income countries. The data on production, imports, and exports were obtained from FAO (1996). GDPs were measured in constant US dollars with data from World Bank (1995). The parameters were estimated by covariance analysis; elasticity examples are in table 1.

In the GOS model, prices are endogenous (the equilibrium between demand and supply leads to the prices). Only national GDPs shift demands, and they are strictly exogenous. Three scenarios regarding GDP growth were assumed. In the median scenario, Africa grew at 3.2 percent per year in 1995, increasing to 3.4 percent in 1996 and then approaching 2.3 percent by 2010. For North and Central America, GDP grew at 1.8 percent per year in 1996, to 2.2 percent by 2010. In South America, growth that began at 1.1 percent in 1995 increased to 3.5 percent in the first years of projection and then declined to 3 percent in 2000 and 2.3 percent in 2010. Asia continued to grow fast in the projections, but at lower rates. Growth began at 8.4 percent in 1995 and then declined progressively to 2.9 percent in 2010. In Europe, growth that started at 2.1 percent in 1996 was assumed to increase to 2.6 percent by 2000 and reach 2.3 percent by 2010. The former USSR projections assumed a progressive recovery, ending with a 2.5 percent GDP growth rate by 2010.

Wood Supply Constraints

A feature of GOS-96 is the application of explicit limits to the supply of timber and other raw materials in each country. The supplies of fuelwood and charcoal, industrial roundwood (logs, chips, particles, wood residues, and other industrial roundwood), other fiber pulp, and waste paper were represented by a reservation price, assumed to be equal to the world price, up to the sustainable production potential. This implies that the cost of production is constant up to the production potential. Costs and prices would then rise sharply when the potential was reached.

The maximum potential roundwood supplies in 1994 and 2010 for three scenarios were set as maximum growth rates, the actual supply could be less depending on

Table 1.—*Examples of elasticities used in the GOS-96 model*

GDP Group	Price	GDP	Lag	Long-term Price	Long-term GDP	R^2	Degrees of freedom
Sawnwood							
High	-0.13	0.15	0.53	-0.28	0.32	0.99	434
	(0.04)*	(0.03)*	(0.04)*				
Low	-0.07	0.19	0.66	-0.21	0.56	0.95	945
	(0.04)**	(0.06)*	(0.03)*				
World	-0.08	0.16	0.65	-0.23	0.46	0.97	1382
	(0.03)*	(0.04)*	(0.02)*				
Printing and Writing Paper							
High	-0.38	0.47	0.54	-0.83	1.02	0.99	415
	(0.06)*	(0.05)*	(0.04)*				
Low	-0.22	0.76	0.42	-0.38	1.31	0.96	793
	(0.04)*	(0.08)*	(0.03)*				
World	-0.25	0.65	0.45	-0.46	1.18	0.98	1211
	(0.03)*	(0.05)*	(0.03)*				

Note: Standard errors of short-term elasticities in parentheses. * significant at 5 percent level, ** at 1 percent.

demand, but it could not be more. Three scenarios were meant to cover the range of possible supplies in each country. They were based on various information (FAO 1995a, UN-ECE/FAO 1993). In total, the growth rate of the world roundwood supply potential was assumed to be about 0.9 percent, 1.3 percent, and 1.9 percent, depending on the scenario. The medium assumption was near those of Brooks *et al.* (1996).

Other Assumptions

Other assumptions governing the projections concerned changes in capacity, fiber input mix, and trade inertia constraints. In PELPS, capacity is governed by past production and by relative profitability. The simplest projection method of PELPS were used. It consisted of distributed-lag functions linking capacity changes to changes in past production at the global level, followed by allocating capacity growth to different countries according to the shadow price (the marginal value of one unit of additional capacity) revealed by the equilibrium computations (Gilless and Buongiorno 1987).

The technology, defined by input-output coefficients was held constant at the 1994 level, except for paper and paperboard. There, it was assumed that the fiber input mix for newsprint, printing and writing paper, and paper and paperboard would change substantially between 1994 and 2010. The share of other fiber pulp would increase from 7.6 to 10.8 percent worldwide, while that of recycled paper would increase from 36.5 to 45.6 percent worldwide, and to nearly 50 percent in Europe. The potential recovery rates were allowed to reach 40 to 60 percent of paper and paperboard consumption, depending on the region. However, the actual recovery rates projected by the model as a result of market forces were lower.

The levels and trends of trade in forest products are determined by a wide range of factors of which only the main elements were recognized—levels of demand, costs of wood, and costs of other factors. With the implementation of GATT-WTO, the member countries should reduce or eliminate trade tariffs and non-trade barriers. However, the adjustment of trade flows is bound to take time, thus inertia constraints were introduced to limit trade in a given year to be within a specified fraction of the previous year's trade (Buongiorno and Gilless 1984, Kallio *et al.* 1987, Zhang *et al.* 1996). The trade inertia in scenario 1 and 2 constrained exports and imports of a country in a given year to be within 5 to 15 percent of that in the previous year. Scenario 3 assumed that trade enhancing policies would be such that the yearly variation of imports or exports could be between 10 and 20 percent.

GLOBAL OUTLOOK TO 2010

The GOS-96 model has been applied to project production, consumption, exports, and imports from 1995 to 2010, under each scenario. The detailed tables by country and product are in FAO 1997. The projections indicate that the global demand for forest products should continue to rise, pulled by the demand in rapidly growing economies, especially in Asia. The total roundwood consumption and production would reach 3.9 billion m^3 by the year 2010, for a median growth rate of 1 percent per year, but faster in the former USSR (table 2). Of this, about 2 billion m^3 would be fuelwood consumed largely in developing countries. World sawn wood consumption, at near 470 million m^3 would be lower in 2010 than in 1990, due to the sharp decline in the former USSR from 1990 to 1994, not fully recovered by 2010. In the rest of the world, sawn wood consumption would be slightly higher than in 1990. Wood-based panels consumption would total 143 to 172 million m^3 worldwide by 2010, growing at an average of 1.6 percent per year in developed countries and 3.2 percent per year in developing countries, with plywood, particleboard, and fiberboard maintaining approximately constant shares. Paper consumption is expected to grow the fastest, averaging 2 percent per year in developed countries and 4 percent per year in developing countries, leading to a world consumption of 360 to 401 million metric tons in 2010.

In 2010, Asia is projected to be the largest net importer, for all products. South America and the former USSR would become the main net exporters of industrial roundwood. North/Central America and the former USSR would be the main exporters of sawn wood, while for panels that role would be taken by South America and the former USSR (fig. 1). Europe and North/Central America would be the main net exporters of paper and paperboard.

Under the medium scenario, the real prices of industrial roundwood, sawn wood, and wood-based panels are projected to change little until the year 2010. The real prices of paper and paperboard would also generally remain constant. Strong price increases were obtained in the scenario assuming the lowest potential timber supply, but even then, paper products would be less affected due to the growth in the world waste paper recovery (fig. 2).

APPENDIX

Mathematical formulation of GOS-96

GOS-96 was built with the general PELPS III structure (Zhang *et al.* 1993). It simulates a dynamic market equilibrium for the global forest sector. Every year, demand, supply, trade, and prices are computed that clear markets for all products and in all regions (static phase).

Table 2.—*Roundwood consumption (thousand m³)*

Region	Actual				Projection		Annual growth	
	1970	1980	1990	1994	2000	2010	1970–1990	1994–2010
							- - - percent - - -	
Africa	255,658	334,514	438,271	489,850	538,570	604,719	2.73	1.33
North/Central America	471,269	605,860	723,735	727,128	754,409	792,060	2.17	0.54
South America	163,968	242,831	294,336	320,328	344,214	378,945	2.97	1.06
Asia	751,328	928,721	1,096,895	1,167,622	1,267,375	1,400,969	1.91	1.15
Oceania	23,724	25,744	31,450	30,487	33,702	36,347	1.42	1.10
Europe	351,027	350,058	402,004	351,742	378,317	411,678	0.68	0.99
Former USSR	369,548	342,020	374,896	122,870	195,288	211,535	0.07	3.45
Totals								
Developed	1,284,409	1,371,870	1,558,801	1,254,615	1,377,090	1,463,757	0.97	0.97
Developing	1,102,113	1,457,878	1,802,786	1,955,412	2,134,785	2,372,496	2.49	1.22
World	2,386,522	2,829,748	3,361,587	3,210,027	3,511,875	3,836,253	1.73	1.12

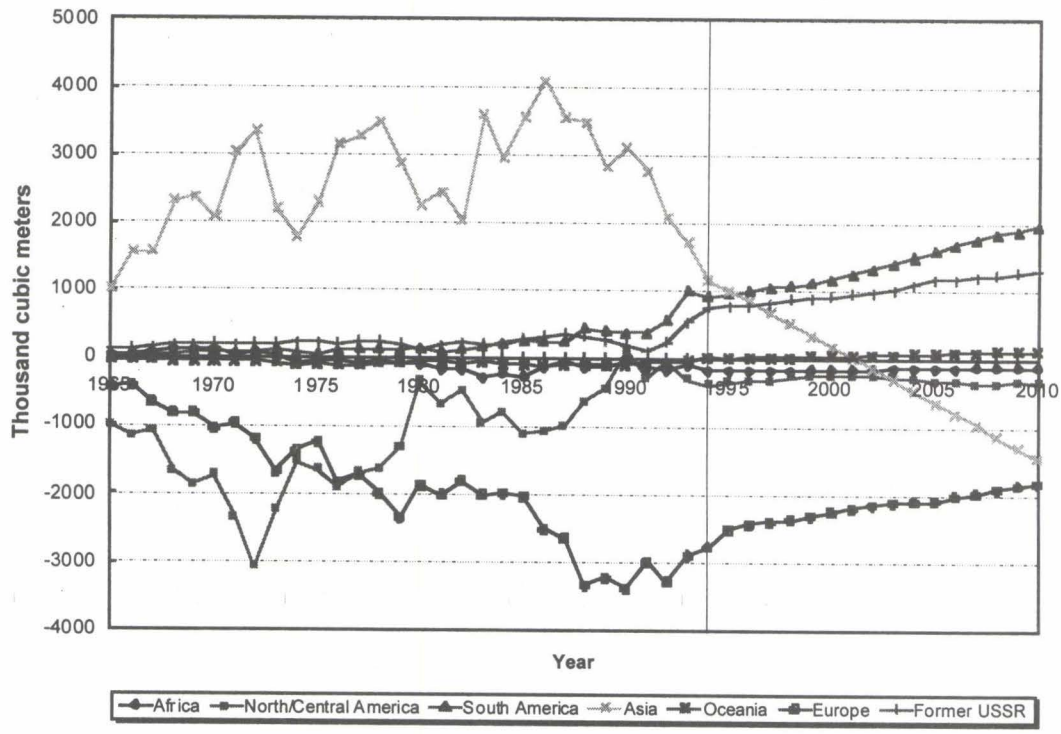

Figure 1.—*Veneer sheets and plywood net trade.*

Then, the model parameters are updated to reflect exogenous and endogenous changes from one year to the next (dynamic phase). Yearly exogenous changes include economic growth, technical change, potential timber supply, and trade inertia—they are assumptions. Yearly endogenous changes include capacity growth and availability of recycled fibers, they are determined by the model. The model then computes the quantity-price equilibrium next year as shaped by the intervening changes. It reiterates the static and dynamic phases for every year until the end of the projection.

Static phase

The equilibrium for each year of the projection is obtained with an optimization model that simulates world markets. It finds the production, consumption, and trade that maximizes the total value of consumption minus the total cost of production for all products in all countries, in a given year. All the variables refer to that year.

Objective function:

$$\max Z = \sum_i \sum_k \int_0^{D_{ik}} P_{ik}(D_{ik}) dD_{ik} - \sum_i \sum_k \int_0^{S_{ik}} P_{ik}(S_{ik}) dS_{ik} - \sum_i \sum_k Y_{ik} m_{ik}$$

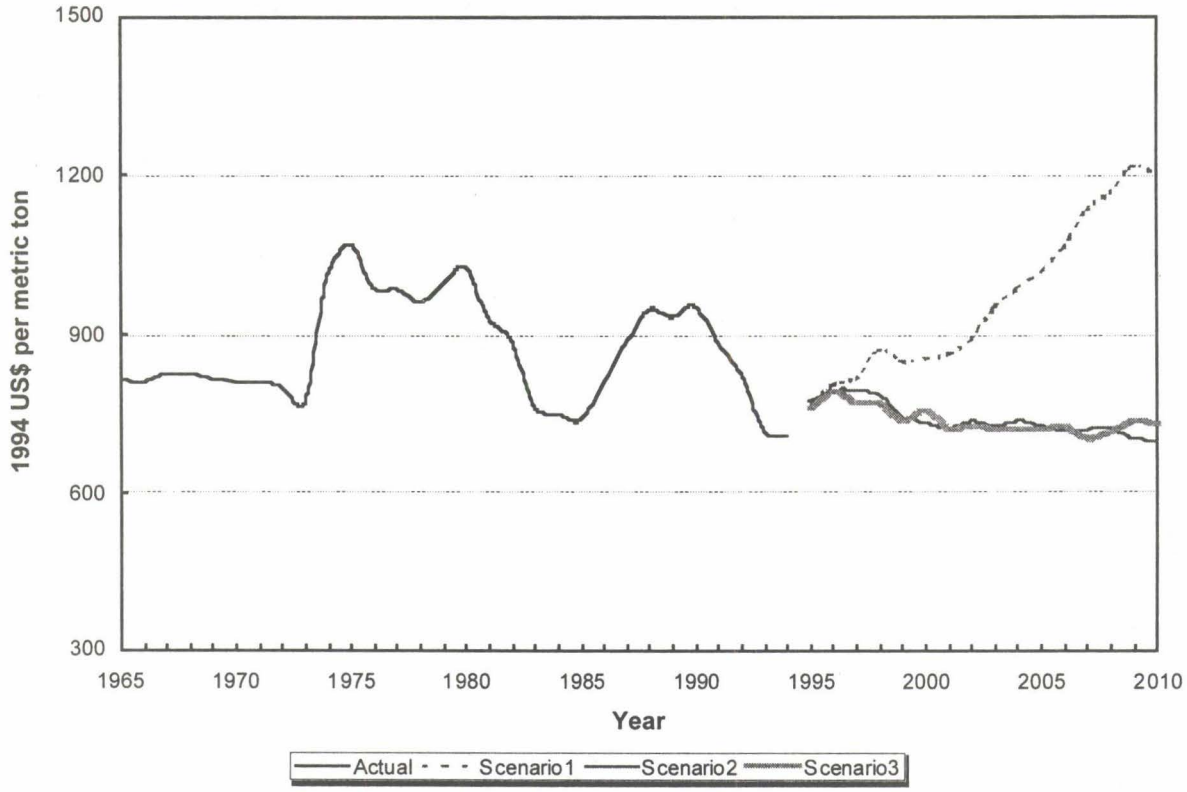

Figure 2.—*Paper and paperboard price.*

where: i,k = country, commodity, P = price in US dollars, D = final product demand, S = raw material supply, Y = quantity manufactured, m = cost of manufacture.

Demand for final products:

$$D_{ik} = a_{ik} P_{ik}^{\sigma_{ik}} X_i^{\alpha_{ik}} D_{ik,-1}^{\eta_{ik}}$$

where: D_{-1} = demand in the previous year, X = gross domestic product, in real US dollars, σ,α,η = elasticities with respect to price, GDP, and past demand.

Wood supply:

$$P_{ik} = P_{ik}^{0} \quad with \quad S_{ik} \le S_{ik}^{U}$$

where: P^0 = cost of production, S^u = potential supply.

Material balance:

$$\sum_j T_{jik} + S_{ik} + Y_{ik} - D_{ik} - \sum_n a_{ikn} Y_{in} - \sum_j T_{ijk} = 0 \qquad \forall i,k$$

$$T_{ijk}^{L} \le T_{ijk} \le T_{ijk}^{u} \qquad \forall i,j,k$$

where: a_{ikn} = input of commodity k per unit of n, T = trade flow. Each country exports to and imports from a "world market", T^u, T^L = upper and lower bounds on imports and exports.

Manufacturing capacity:

$$Y_{ik} \le K_{ik} \qquad \forall i,k$$

where: K = current capacity of production.

Waste paper recovery:

$$S_{ir} \le S_{ir}^{U} \qquad \forall i,r$$

where: r = recycled paper, S^U = upper bound on recycled paper supply.

Dynamic phase

Yearly changes in the market equilibrium constraints are brought about by:

1) shifts of the demand curves, due to changes in X at the projected GDP growth rate,

2) shifts of the upper bounds on wood supply, S, at the assumed rate of growth of potential supply,

3) changes of manufacturing coefficients m to reflect technical change, especially increasing use of paper recycling,

4) changes of capacity, determined as follows: At global level, capacity change is a function of changes in production during the past 3 years:

$$\Delta K_k = b_{1k} \Delta Y_{k,-1} + b_{2k} \Delta Y_{k,-2} + b_{3k} \Delta Y_{k,-3}$$

then, global capacity change is allocated to each country in proportion of its production level and the marginal value of capacity revealed by the shadow price of capacity in the static phase.

$$\Delta K_{ik} = \frac{Y_{ik}^{\theta} \pi^{\varpi}}{\sum_{j} Y_{ik}^{\theta} \pi^{\varpi}} \Delta K_k$$

where: Δ = yearly change, π = shadow price of capacity (endogenous, from capacity constraint), b, θ, ϖ = parameters.

5) Changes in waste paper recovery:

$$S_{ir}^{U} = \sum_{k} w_{ikr} D_{ik,-1}$$

where: w_{ikr} = maximum possible recovery rate (exogenous).

6) Trade inertia:

$$T_{ijk}^{u} = (1+\varphi) T_{ijk,-1} \quad and \quad T_{ijk}^{L} = (1-\varphi) T_{ijk,-1}$$

where φ = upper bound on relative change in trade flow (exogenous).

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LAKE STATES TIMBER SUPPLY AND ANALYSIS MODEL: LASTISA

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ABSTRACT.—The Michigan prototype for a timber stumpage supply model for the Lake States is designed to project timber supply by forest type, ownership, geographic region, and product through 2020. The model is composed of inventory, growth, harvesting, management, yield, timberland availability, and output modules. Results include estimates of timber inventory and harvest trends and distributions among ownerships and forest types.

INTRODUCTION

The Lake States Timber Supply Analysis (LASTISA) is a cooperative research project among researchers at Michigan State University, Department of Forestry and the North Central Forest Experiment Station, USDA Forest Service, East Lansing, MI (Leefers *et al.* 1997). The objective is to develop analytical supply models for major forest types in the Lake States (Michigan, Minnesota, and Wisconsin). The structure of the LASTISA model is discussed below and initial results from simulations of the aspen cover type are presented for Michigan.

Background

As in many parts of the United States, timber supply is an important issue in the Lake States. The most recent forest inventories (1983 for Wisconsin, 1990 for Minnesota, and 1993 for Michigan) show that there are 47.4 million acres of timberland in the region. Most of this timberland is in non-industrial private ownership (55 percent). Public ownership is also significant (13 percent federal, 15 percent state, and 10 percent county), while forest industry holds 7 percent. The patterns of ownership vary across the region, however, all states contain significant interspersed state, federal, industrial, and non-industrial private lands. Lake States' forests are remarkably diverse and dominated by stands characterized by multiple ages and mixed species. A wide range of timber products are harvested ranging from softwood and hardwood pulpwood to very high value veneer logs. The timber supply problem in the Lake States requires consideration of multiple ownerships, diverse forest types, all-aged stands, multiple products, and sub-regional production areas.

The primary research need is for a regional model capable of accounting for timber growth and projecting changes in timber supply due to shifts in harvesting and management practices and availability of timberland for harvest.

Harvest levels have steadily increased for the past several decades. Pulpwood production in the Lake States was 8.7 million cords in 1995. This production is 2.22 times that of 1970 (Vasievich *et al.* 1996). Total saw log production also increased since the mid-1970's to a mid 1990s level of 1.6 billion board feet (3.3 million cord equivalents). Sawtimber trends, however, are more difficult to identify, due to sparseness of common measurement data across the Lake States.

Objectives

The objectives of the LASTISA supply modeling project are to: (1) predict the volume (ft^3) of growing stock timber in each forest type for 5-year periods from 1995 to 2020 and for each sub-state region of the Lake States; (2) predict how the inventory is allocated among physical products in each projection period for each sub-state region; and (3) project the potential timber inventory impacts of changes in timberland available for harvest by ownership, harvest practices, and management strategies.

LASTISA—A STAND-LEVEL MODEL

Framework

LASTISA is an aggregate stand-level inventory model for projecting available timber supplies and simulating effects of management. Simulation units (SUs), or

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aggregates of similar stands, are the operational units of the model. Simulations are performed through manipulation of simulation units through growth, yield, timberland availability, and harvesting sub-models (fig. 1). Databases from the USDA Forest Service Forest Inventory and Analysis (FIA) periodic inventories of Lake States forests form the basis for the stand simulation unit records and the development of empirical growth and yield equations used by the model.

LASTISA was developed to meet the following predetermined performance criteria:

1. Models should be based on empirical data.
2. Required data should be readily available to timber supply researchers and analysts.
3. Models should be conceptually sound with respect to biometric relationships.
4. Model calculations should be operable on a desktop microcomputer.
5. The number of equations required should be small.
6. Volume projections should achieve an acceptable level of accuracy.
7. Models should adequately reflect the mixed-age and mixed-species forest types common in the region.

These criteria led the authors to develop an empirical model based on recent FIA data rather than adapt existing age-class based models such as ATLAS (Mills and Kincaid 1991) or SERTS (Cubbage *et al.* 1991).

Simulation Units

Unique SUs represent groups of similar areas and are defined by FIA unit, forest type, site index class, basal area class, and ownership (table 1). FIA units (fig. 2) provide the geographic context for analysis since they reflect logical boundaries of sub-state projection regions. Sorting of the 1993 Michigan FIA data into SUs produced 3,042 simulation units, averaging 6,099 acres. Areas for Michigan SUs ranged from 200 to 94,000 acres. Each SU record carries associated values for mean basal area (ft^2/acre), mean site index (feet at 50 years), area (acres), and mean age (years). These variables are used for growth, yield and harvest calculations, and reports.

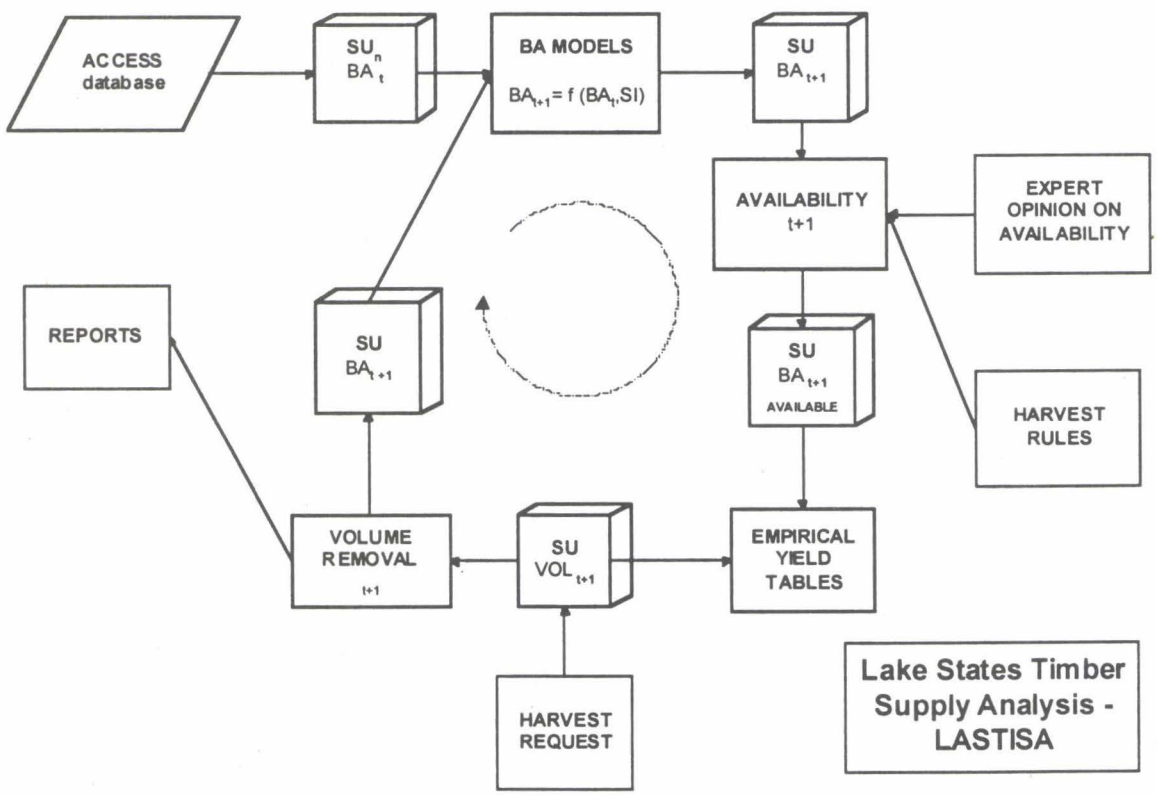


Figure 1.—*LASTISA model components.*

Table 1.—*Stand characteristics defining simulation units*

Region —FIA unit	Forest type	Ownership	Site index class (feet at 50 years)
Michigan	White-Red pine	National Forest	< 26
Western UP	Jack Pine	State forest	26-35
Eastern UP	Upland conifers	County/Municipal	36-45
Northern LP	Oak-Hickory	Other federal	46-55
Southern LP	Lowland hardwoods	Forest industry	56-65
Minnesota	Maple-Beech-Birch	Non-industrial private	66-75
Northern Pine	Aspen-Birch	(and other industrial)	76-85
Aspen-Birch	Lowland conifers		86-95
Central-Hardwood	Nonstocked		>95
Prairie			
Wisconsin			
Northwest unit			
Northeast unit			
Central unit			
Southwest unit			
Southeast unit			

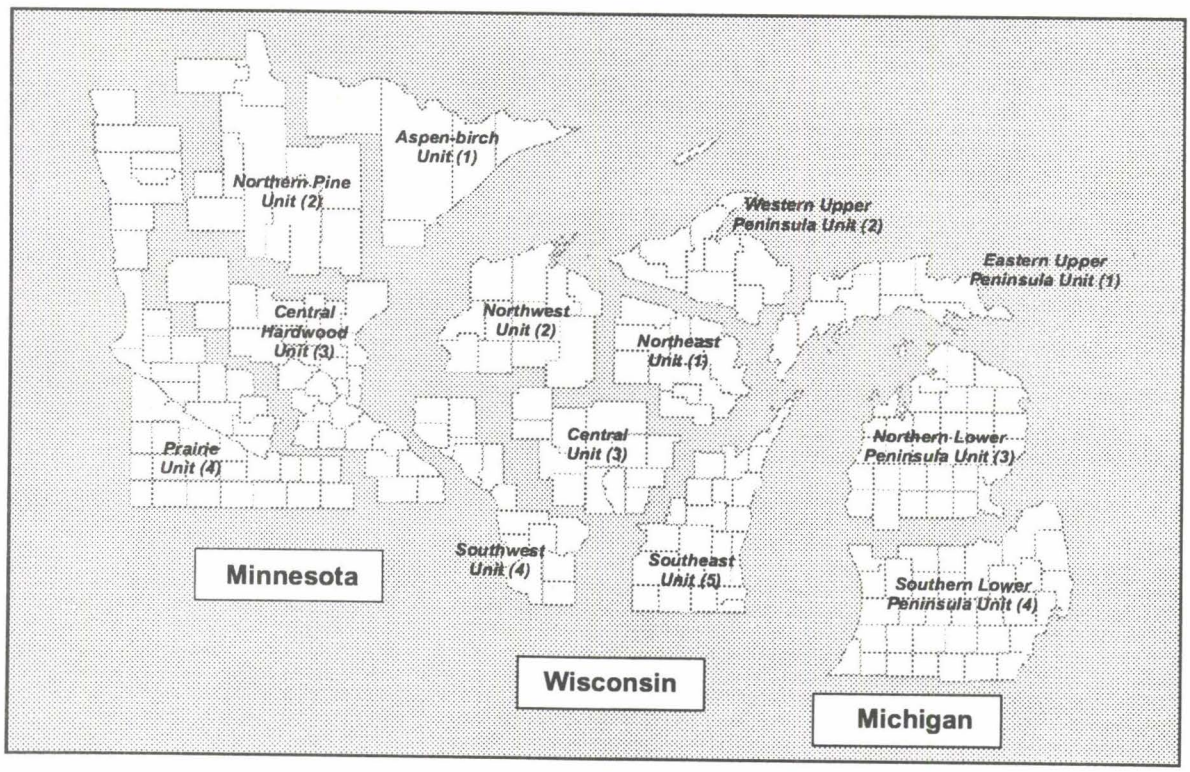


Figure 2.—*FIA units in the Lakes States study region.*

Basal Area Growth Model

The FIA data set was used for net basal area growth model development due to its data richness, ready availability, and comparability across the region. Models were developed first for Michigan to verify model form and for testing purposes. The modeling database consisted of re-measured plots extracted from the 1980 and 1993 Michigan FIA data. The records in this database were a sub-sample of the simulation unit database described above.

Empirical growth models were developed for each of the nine forest types to estimate net change in basal area from the first inventory cycle (1980 for Michigan) to the second (1993 for Michigan). This design, as opposed to one based on age classes, was chosen in order to better reflect uneven-aged stands and partial cutting. Also, individual tree models, such as STEMS (Belcher *et al.* 1983), were not used to reduce data requirements in this aggregate stand model. Descriptive statistics were calculated and plot data graphed. Initially non-linear models were investigated but unsuccessful results led the researchers to examine multivariate linear models[2]. Several multivariate linear models were built for each forest type. Models were examined for adjusted R^2, standard error and F statistics (α= 0.05). The best model form for all forest types was determined to be $BA_1 = b_1(BA_0) + b_2(SI_{spp})$, where BA_1 is basal area in cubic feet for time period two; BA_0 is initial basal area, and SI_{spp} is the site index for the dominant species. Adjusted R^2's for the models ranged from 0.941 to 0.994. Examination of residuals showed no problematic patterns.

Yield Models

Empirical yield models were also developed for each forest type from the Michigan FIA database. The purpose of these relationships is to estimate standing and harvested volume for each forest type. The most recent inventory (1993) for Michigan was used to estimate regression equations relating basal area to merchantable pulpwood volume (cords), sawtimber (MBF) and total volumes (cords). To estimate yield equations, data derived from FIA plot records were fit for the model $Y = bBA + \varepsilon$ where Y is the yield component and BA is the plot basal area (square feet). Although simple linear relationships are quite good for the aspen-birch type ($R^2 > 0.95$), other model forms are better for other forest types. Further refinement of these yield models is in progress to more accurately fit the data. Regression results for the aspen-birch forest type are presented in table 2.

Table 2.—*Linear yield coefficients (basal area) for the aspen-birch forest type in Michigan*

Product	Units	Basal area coefficient
Total Yield	cords	0.22805
Pulpwood	cords	0.13981
Sawtimber	MBF	0.04330

Timberland Availability

Timberland available for harvest plays an important role in determining the sustainability of timber production in the Lake States. The Lake Sates Forestry Alliance (1991) identified factors influencing forest use trends in the Lake States: (1) demographic change, (2) resource trends, (3) technologic developments, (4) economic forces, and (5) geopolitical forces. Resh (1994) asked resource managers to quantify the implications of these forces on the availability of timberlands for harvest on various ownerships in the Lake States. Over 300 responses were received. Although the range of responses was wide, on average, more than one-quarter of the current timberland base is perceived as being unavailable for harvest due to constraints related to management objectives (table 3). This figure is expected to increase in the future. Availability, as a function of ownership, location within the region, and time, is an exogenous variable in LASTISA. The percentage of timberland available for harvest in each SU can be reduced to enable simulations of alternative scenarios. This construct in the LASTISA model provides a mechanism to estimate the supply implications of management constraints on harvests.

Harvesting

Harvest requests are exogenous to the model to allow for testing the effects of different production requirements on inventory. For Michigan, researchers set requests to historic levels as determined by Timber Product Output reports of the USDA Forest Service (May and Pilon 1995). The harvest requests for each 5-year projection period are processed first on the basis of proportional harvest shares among ownerships derived from FIA data. If the request cannot be met, the model searches for volume available on the SUs richest in basal area on other ownerships. That is, unmet harvest requests are spread proportionally among other ownerships, drawing the most from the SUs with greatest stocking. These shifts in harvest shares are one of the main features of LASTISA reports.

[2] *The authors gratefully acknowledge the assistance of Carl Ramm, Department of Forestry, Michigan State University in the development of the net basal area growth models and the suggestions of Joseph Buongiorno, Department of Forestry, University of Wisconsin-Madison.*

Table 3.—*Timberland availability estimates for Michigan*

Ownership class	Sub-state region or FIA unit	Estimated percent availability (from Resh 1994)	
		1994-1995	2020
State	Eastern Upper Peninsula	70	59
State	Western Upper Peninsula	81	70
State	Northern Lower Peninsula	78	67
State	Southern Lower Peninsula	66	60
NIPF	Eastern Upper Peninsula	78	72
NIPF	Western Upper Peninsula	79	68
NIPF	Northern Lower Peninsula	65	59
NIPF	Southern Lower Peninsula	87	79
Industry	All regions	90	90
National Forest	Eastern Upper Peninsula	52	46
National Forest	Western Upper Peninsula	61	51
National Forest	Northern Lower Peninsula	55	49

Simulation models usually apply prescriptive (i.e., normative) or descriptive (positive) harvesting rules. In the first instance, normative harvest rules can be used to predict the implications of specific silvicultural guidelines. The alternative is to craft positive rules which describe the actual patterns commonly used on different ownerships or in different regions. Harvest rules can be based on any combination of SU attributes, such as basal area stocking, forest type, location, ownership, site index, or mean stand age. Harvesting rules used by LASTISA describe how to select SUs for harvesting and how to change the attributes of the SU to simulate harvests and volume production. For normative rules the researchers reviewed and compiled prescriptions from sources such as USDA Forest Service Managers' Handbooks (e.g., Brinkman *et al.* 1975, Perala 1977). Rules were written for each prescription which translated harvests to prescribed residual basal area or percent basal area of the stand removed. For positive harvest rules, management practices from public lands were compiled and the practices similarly translated into basal-area based rules. After harvest removals are calculated, the SU records are updated to reflect new inventory conditions. Then the cycle is repeated for the next 5-year period until the year 2020 is reached. For the initial testing phase, harvests were allowed only if basal area exceeded a minimum amount. The capability to apply a variety of harvest rules enables users to test a wide range of harvest strategies with the LASTISA model.

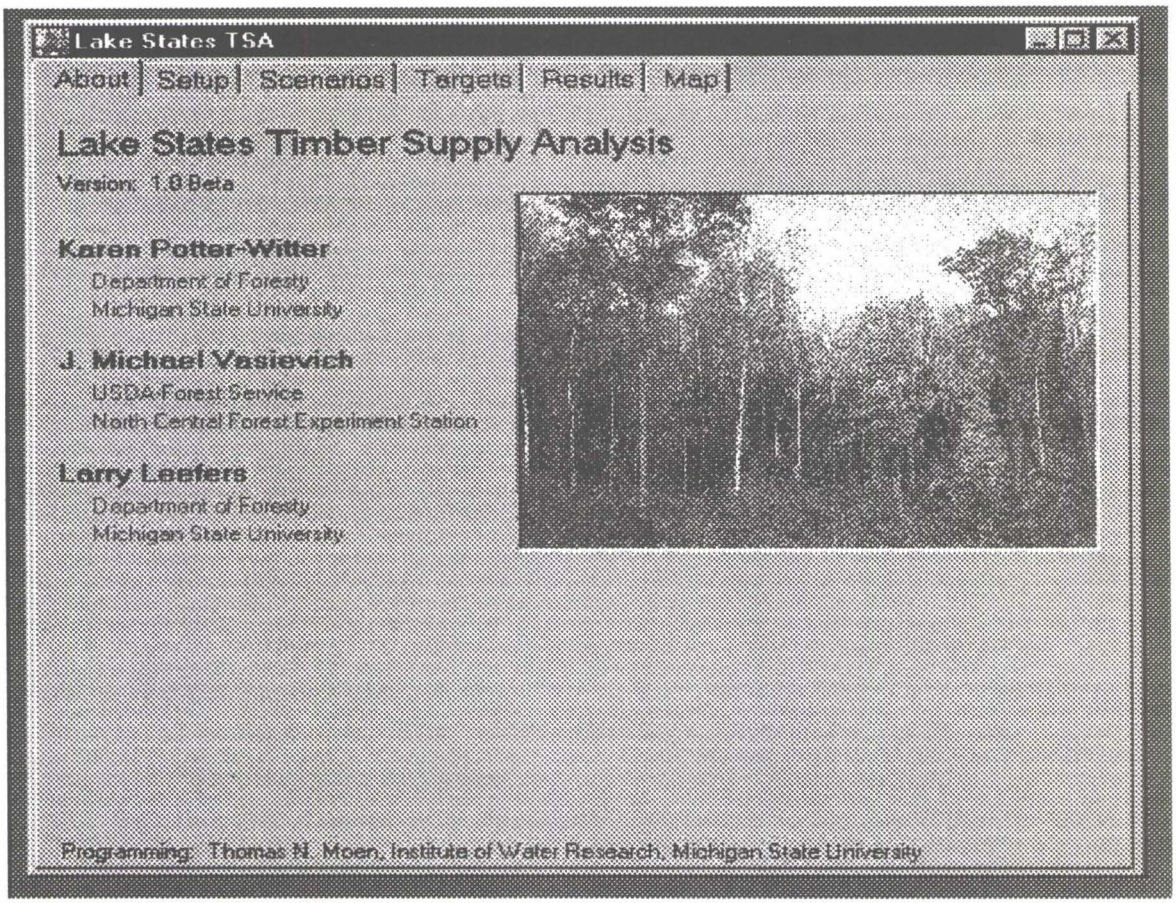
RESULTS

The initial implementation of LASTISA was developed using Microsoft Visual Basic 5® (fig. 3). The aspen-birch forest type, which totals over 3.1 million acres in Michigan, was used for the initial trials. Harvest targets were based on historic timber production trends. The 5-year production level of 5.5 million cords (combined pulpwood and saw logs) was set as a constant harvest level for each production period. Four FIA units in Michigan were modeled and volumes harvested were calculated for each SU. Ownerships included were: national forests, state forests, county/municipal forests, other federal forests, forest industry, and non-industrial private forests. Harvests were modeled for five 5-year projection periods (i.e., 1996-2000, 2001-2005, etc.). Shifts among ownerships for aspen-birch supply were allowed every 5 years, if needed. Reductions in timberland availability for harvest were included for the initial trials.

Results showed that the 5.5 million cords 5-year harvest request from the aspen-birch type was met for each of the projection periods (fig. 4). Harvest shares, however, shifted over time as timber became less available on public lands. In 2010, state forest lands could not meet their harvest request share, and the NIPF share increased. State forest share increased for the 2015 and 2020 periods, but still did not reach their 2000 levels. These results are likely due to two factors—an unbalanced age-class distribution for aspen-birch forests, and changes in anticipated timberland availability. In a similar fashion, national forests show a decline of aspen-birch timber harvest over time due to reduced availability.

CONCLUSIONS

LASTISA is an empirically based timber supply model with major components that are often missing in other models. Notably, it is designed to model shifts in supply


Lake States TSA
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Lake States Timber Supply Analysis
Version: 1.0 Beta
Karen Potter-Witter
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North Central Forest Experiment Station
Larry Leefers
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Michigan State University
Programming: Thomas N. Moen, Institute of Water Research, Michigan State University

Figure 3.—*LASTISA.*

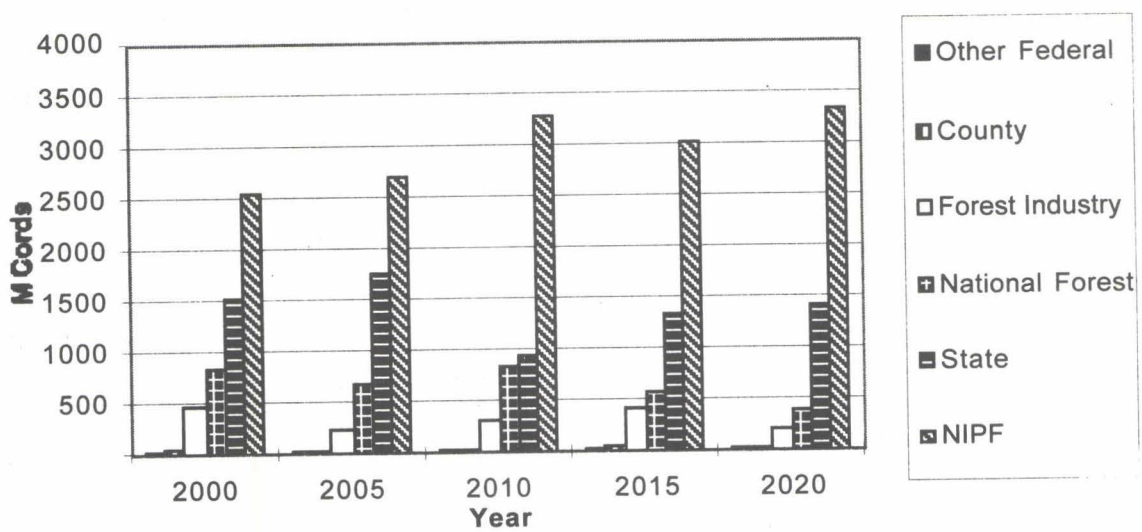

Figure 4.—*Estimated aspen harvest by ownership and year.*

from one ownership to another. This provides a better approach for assessing regional supply which often depends on individual ownerships' management plans. LASTISA explicitly incorporates timberland availability changes so that expert's views of their implications can be modeled. Unlike other aggregate timber supply models, LASTISA's growth and yield projections are based on basal-area growth and yield models developed from empirical data rather than an individual tree model of even-aged stand.

Initial results of simulations from the LASTISA model are promising. They demonstrate the potential of the model for testing the effects of differences among ownerships and harvest policy on timber supply. The LASTISA model continues under development. Additional work to extend the model to the full set of Lake States production regions and to validate model performance is in progress.

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MODELING THE REGIONAL ECONOMIC ASPECTS OF FOREST MANAGEMENT ALTERNATIVES

David W. Marcouiller and Jeffrey C. Stier[1]

ABSTRACT.—Regional economic assessments of forest management alternatives provide complex modeling problems for policy analysts. Two specific empirical complexities involve income distribution and output trade-offs within a market-based neoclassical economic framework. This paper develops a social accounting matrix (SAM) model to investigate distributional impacts and differential outputs of alternative forestland management regimes of the Upper Great Lakes forested region. Extensions to computable general equilibrium (CGE) models are outlined. Whereas SAMs provide a comprehensive empirical accounting structure, they lack market-based prediction ability. CGE models are better equipped to handle markets but lack an empirical basis for parameter estimation.

INTRODUCTION

As we increasingly strive to manage forests for a wide range of goods and services, we affect the structure of local economies in rural forested regions. This has important implications for both those who reside within forested regions and societally demanded forest-based public-goods benefits. In rural forested regions, timber resources provide important raw material inputs into regional value-added activities of wood products manufacturers and regional tourism interests. Policies that address forest resources from a regional perspective are typically analyzed in fixed-price aggregate terms using economic measures such as total number of jobs created or total change in regional income measures. The contributions of forest resources to regional development, however, are more complex.

Shifts in forest use can have important impacts on regional economic linkages and the manner in which income is generated and distributed to regional households. Thus, one type of complexity involves the distribution of benefits by household income level (Wear and Hyde 1992). Also, alternative forest management regimes use different combinations of land, labor, financial capital, and growing stock inputs. Management choice of input combination determines output levels of both private goods (timber stumpage) and public goods (recreational values, non-use values, etc.) Thus, another important aspect of regional development that represents the complex nature of forest resource impacts is the differential production of nonpriced public goods under alternative management regimes (Hyde and Amacher 1996, Bostedt and Mattsson 1995) and the resulting dilemma of who benefits and who pays for the production of public goods (Piggott and Whalley 1991).

This paper investigates analytical options used to model distributional impacts and differential outputs of alternative forestland management regimes. We limit the discussion to two contemporary regional science methodologies. First, we construct and critique a small stylized social accounting matrix (SAM) of the forested Upper Great Lakes States economy. In doing so, however, we identify a general inability to capture production differences and resulting factor market influences as a primary shortcoming. These influences lead us to seek more flexible modeling choices. Extensions into more flexible techniques that model regional factor substitution among forest management regimes will be outlined. A plausible single-region computable general equilibrium (CGE) model will be outlined that elaborates markets and appropriate policy questions.

[1] **David W. Marcouiller** and **Jeffrey C. Stier** are with the University of Wisconsin-Madison, Departments of Urban and Regional Planning and Forest Ecology and Management, respectively. This project is funded through the McIntire Stennis program of the USDA. We wish to thank Steve Deller and John Wagner for insights and linkages to a companion project funded by the USDA National Research Initiative.

CORE SET OF PROBLEMS

In developing a more general framework to assess forest management, we begin by noting that the level of management intensity determines both income distribution and output trade-offs. Thus, modeling the regional economic impacts of forest production alternatives requires a focus on critical issues of management intensity. Forest managers implicitly choose alternative silvicultural regimes based on landowner objectives. Although difficult to generalize, the range of alternatives varies from optimal fiber production using even-aged silviculture to reliance on fully natural, nonsilvicultural, options. To many, the level of silvicultural input would provide a basis for defining "intensive" forest management. It is the choice and application of a management alternative that dictates the use of production inputs; results in income being generated and distributed to owners of primary factors; and determines both the type and extent of forest outputs.

Although past research has identified production differences among land ownership groups (Newman and Wear 1993, Wallace and Newman 1986), we have few standard definitions for characterizing the "intensity" of management. Any definition of management intensity would need to be based on how landowners combine production inputs to produce output. On the one hand, intensive silviculture would most likely relate to methods designed to increase productivity by expending more labor and capital rather than by increasing the scope (or the use of land inputs) of production. On the other hand, extensive silviculture might constitute growing trees using large tracts of land with minimal expenditure of labor or capital. There is a considerable amount of confusion, however, over what measures we could use to characterize this type of management intensity.

This simple static definition of management intensity has some serious shortcomings. Primary among these is the notion that growing stock is a dynamic, not static, input into the production of timber. Dismissing nonsustainable options, definitions of intensity must somehow incorporate the growth of and removal from growing stock assets over time. In addition, the initial and residual conditions of growing stock need to be specified. If not accounted for, satisfying an intensity definition would not allow us to distinguish output trade-offs among alternatives. A good example of this is the inability to distinguish outputs among two dichotomous intensive silvicultural options: even-aged and uneven-aged silviculture.

In an intensive even-aged silvicultural regime that begins with bare land, foresters plant genetically improved seedling stock at optimal spacing to provide for fully stocked conditions. Over time, competition is controlled, seedlings grow, the canopy closes, intermediate thinnings are timed and applied so that optimal spacing is maintained, multiple timber products are removed, and, ultimately, the stand is returned to bare land to start the process over again. Here, growing stock is initially zero and ultimately returns to zero. Growing stock accumulates based upon the financial and biological growth characteristics determined through management input. While it is an efficient way to produce private goods (timber), many argue that this alternative generates low levels of public goods (aesthetics, biodiversity, and recreational value).

The alternative regime utilizes high initial levels of growing stock and maintains these stocks through uneven-aged silvicultural techniques. The maintenance of a perfectly J-shaped diameter distribution through regular selective harvests could attain high financial private yields per acre in timber, thus falling within our input-based definition of intensity, but the type and extent of outputs could be very different. Proponents of this type of silvicultural option point to high output values of public goods. Even- and uneven-aged silviculture options generate very different stand conditions, yet could indeed generate similar timber values. Thus, the question remains: how do we characterize management intensity? Certainly, models that continue to treat forest management practices as homogeneous are gross oversimplifications of reality and, when used for policy analysis, lead to erroneous results and biased implications.

Many of the core policy and planning questions that deal with forest management incorporate more than maximum financial return to timber products generated. There are sets of less tangible benefits to forest management that are overlooked in strictly market-based financial analysis. These include biodiversity, spatial disturbance patterns, and recreational benefits. The key issues for policy analysis include integrating these less tangible, societally determined benefits into the economic assessment of management alternatives. For this paper, these translate into how we model shifts in management policy between extractive and nonextractive uses.

Another modeling problem needs to account for both markets of goods and services as well as factors of production. The factors of production we consider include land, labor, financial capital, and growing stock. Intensive and extensive management regimes utilize these factors of production in different combinations. What effect do shifts in management policy have on initial factor endowments, factor prices, and residual factor endowments? Given that returns to factors of production accrue to owners of these productive factors, how do management alternatives generate and distribute income?

Finally, a core modeling problem deals with how to incorporate output trade-offs associated with alternative management regimes within a policy analysis model. This is particularly acute for nontimber management objectives, outputs of which include common property public goods. Is there a transfer of benefits that accrue to those outside of the forestry production process, perhaps to regional tourism firms? What is the opportunity cost associated with financial nonoptimality? Who benefits from financial nonoptimality? How do we account for the opportunity cost associated with timber management at less than financially optimal levels? Are there opportunities to shift the incidence of public-goods production costs onto those who benefit. If we were able to accomplish this, how would the production and use of public goods be impacted? These are questions left unanswered by current policy models that require further research. Though only partially complete, the following discussion outlines two methods that have potential to address some of these issues.

METHODS

Literature on the economic development of forested regions has included (1) the identification of forward and backward industry linkages (Sartorius and Henle 1968), (2) export-based theory of forest product-led regional growth (Connaughton *et al.* 1985, Schuster and Medema 1989), and (3) analysis of forested regions using input-output methods (Flick and Teeter 1988, Pedersen *et al.* 1989). Recent literature has tied development of forested regions to questions of income distribution (Rose and Davis 1988) and factor market equilibrium (Boyd and Hyde 1989, Daniels *et al.* 1991).

From a regional economic modeling perspective, two related methods appear to have promise in their ability to address the core set of issues identified above. These include an extension of input-output analysis known as SAM analysis and its extension as a base data set for regional CGE models. In this section, we empirically estimate and critique a SAM for the Upper Great Lakes States forested region that specifies two alternative forest production regimes. We then address the ability to extend this SAM into more flexible forms through a single-region CGE model.

A Social Accounting Matrix Approach

The estimation and analysis of SAMs have developed a significant following during the past 25 years.[2] However, there have been few applications of SAM analysis to natural resource-based income distribution (see, e.g., Rose and Davis 1988, Marcouiller *et al.* 1995).

Analytically, rows of the SAM track receipts (revenues) and columns track expenditures. In producing output, production sectors use and compensate factor inputs specified as labor, capital, and land. These factors are compensated through forestry and non-forestry enterprises. Furthermore, forestry is disaggregated into timber production and wood processing activities. Timber production enterprises are then disaggregated into industrial private, nonindustrial private, and public ownership categories. Households receive compensation from enterprises and are disaggregated by income group. The balanced SAM equates regional receipts with respective regional expenditures.

Transforming the SAM into a predictive model requires several steps. Cohen (1988) discusses these as (1) subdividing the SAM into exogenous and endogenous accounts, (2) expressing flows as average propensities of their corresponding column totals, and (3) generating multipliers through matrix inversion. Technical coefficients from the production accounts through the household accounts of the SAM are calculated in a_{ij} form where a_{ij} is calculated as z_{ij}/X_j and denotes the flow, z_{ij}, (measured in dollars of value) from SAM sector i to SAM sector j, and X_j is the total gross output of SAM sector j.

Our empirical SAM focuses on a 101-county region delineated based upon the extent of forest area. It basically covers northern Minnesota, northern and central Wisconsin, and the Upper and Northern Lower Peninsulas of Michigan. This represents the Lake States forested region and encompasses the majority of regional growing stock, commercial harvesting activities, and wood processing facilities. Furthermore, it represents a relatively homogenous region based upon tourist type characterized by general outdoor recreation and nature-based tourism demand. The region is predominantly rural with Duluth/Superior included as the primary standard metro statistical area (SMSA) located within the regional boundaries. The Twin Cities of Minnesota; Madison and Milwaukee in Wisconsin; Chicago, IL; and Detroit, MI are located outside of the regional boundaries. We believe this regional delineation to be useful for developing a more focused analysis of rural forested regions.

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[2]*Regional input-output analysis is a fundamental tool used in sectoral analysis of regional economies (Richardson 1985, Miller and Blair 1985). Extending input-output to SAM analysis is more recent (Pyatt and Round 1985, deMelo 1988, Pyatt 1988). This extension is the result of general dissatisfaction with sectoral input-output analysis in the estimation of regional economic development criteria (Pyatt and Round 1985, Keuning and DeRuijter 1988). SAMs are used to more fully analyze regional economic development (Cohen 1988, Cole* et al. *1989) with particular emphasis on the distribution of income (Adelman and Robinson 1986, Esparza 1989).*

In short, data sources used in the construction of the Lake States SAM include an IMPLAN (IMpact analysis for PLANning) hybrid input-output model (Minnesota IMPLAN Group, Inc. 1996), forest inventory data (USDA Forest Service 1996), 1993 forest product prices, household income distributions (Rose and Davis 1988, USDC 1996) wage rates, transfer payments (USDC 1996, Peterson 1991), and factor shares (Koh 1991, Robinson *et al.* 1991, Marcouiller *et al.* 1996). The SAM is balanced using a current accounting framework which incorporates rest-of-world linkages. A full discussion of the estimation procedures used in constructing the Lake States SAM would extend beyond the page limitations of this manuscript and is available from the authors.

Alternative forest management regimes would be expected to (1) use different combinations of factors based upon ownership patterns and (2) generate income from these factors at different rates of return. Returns to timber production vary among owners of land, labor, and capital with private forest owners being characterized by both high factor shares for human inputs and high rates of return on their investments in land and capital. In contrast, public forest lands provide lower rates of return on land and capital due to nontimber objectives. These differences largely reflect the alternative management intensities (regimes) within which timber is produced. Conceptually, this approach makes the regional linkages between growing stock and non-timber goods explicit. Stand management financial analysis shows a strong positive relationship between level of forest management intensity and output of private goods. It would be reasonable to also forward an inverse relationship between level of forest management intensity and output of nontimber goods. For this work, the framework for empirically estimating a regional opportunity cost for non-timber management objectives adapts and extends an earlier factor shares method for timber production (Marcouiller *et al.* 1996). It involves the allocation of net returns to factor inputs of land, labor, and capital. The data used in this analysis include regional value-added estimates, national labor-output ratios for timber production, average regional wage rates, regional forest inventory data (including silvicultural treatments), and commodity price data. Rental rates are imputed for two separate factors (bare land and capital growing stock). Empirically, these values are estimated using the form:

$$(1)\quad OC_f = \Sigma[(i_{max}(SV_t+KV_t) + qLV_{max}) - VA_t] \quad (t = 1,..., c),$$

where opportunity cost for nontimber forestry production (OC_f) is simply the sum across tenancy groups (t = 1, ..., c) of the differences between returns experienced by the management regime with the highest financial return and the current management regime of each tenancy group. This opportunity cost by land tenancy group is calculated using the maximum imputed rate of return (i_{max}) for land and capital assets applied to the values of factor stocks by tenancy group t where SV_t is bare land value and KV_t is the wholesale value of growing stock. Annual value of labor resources used in the timber production regime yielding maximum imputed rates of return for land and capital assets (LV_{max}) is used to represent the flow component of labor adjusted using the ratio of acreage in the assessed regime to the maximum yield regime (q). The returns to foregone production are represented by estimates of annual value added by tenancy group (VA_t).

For ease of calculation, the return experienced by industrial forest owners can serve as a proxy for the maximum rate of return. Assuming that the value of nontimber goods and services produced by industrial private forest owners is zero, the value of foregone production can thus be inferred for other ownerships. Obviously, assigning industrial private lands zero value for nonmarket goods (done to provide an analytical base) totally overlooks the potential nonmarket goods that are produced on these lands, which, in many cases, are quite significant. Further refinements are needed to correct for this oversight. The empirical factor share/opportunity cost analysis for the 101 Great Lake States' counties making up this forested resource-dependent region is presented in table 1.

Clearly, the use of opportunity costs as a proxy for the value of the public goods represents a first approximation to the true value of the public goods produced by the forest resource. Work by Willis (1990) on assessing the public-goods value of farm land converted to wildlife refuge suggests that the frame of reference adopted and the technique employed for valuation can greatly alter the dollar value of the public goods. He found that contingent valuation (expressed preferences) placed a much higher value on public goods, when compared to opportunity costs, while the travel cost method (revealed preference) resulted in a much smaller valuation. The goal of this current effort, however, is not to determine the correct valuation measure of the public-goods aspect of the forest resource, but rather to determine if ignoring public goods in regional analysis alters our policy recommendations.

Factors are compensated through forestry and nonforestry institutions. Furthermore, forestry is disaggregated into timber production and wood processing activities. Timber production institutions are then disaggregated into industrial private, nonindustrial private, and public ownership. Recreation-related institutions include eating/drinking, hotel/overnight accommodations, and related services. Households receive compensation from institutions and are disaggregated into three groups based on annual household

Table 1. —*Regional factor shares, imputed rates of return, and opportunity costs by land tenancy group (USDA 1996, Mercoullier* et al. *1996)*[a]

Tenancy Group	Timberland acreage	Value added[b] per acre 1993	Imputed[c] rate of return to land and capital	Factor Share			Opportunity cost1993
				Land	Labor	Capital	
	Million acres	*Dollars*	*Percent*		*Proportions*		*Million dollars*
Industrial private	3.4	4.72	1.8	0.39	0.22	0.38	0.0
National forest (public)	5.6	3.45	0.9	0.26	0.49	0.25	7.1
Other public	11.7	2.39	0.8	0.33	0.42	0.25	27.5
Nonindustrial private	18.8	2.43	0.9	0.32	0.38	0.30	43.0
Total/All owners	39.5	2.76	0.9	0.33	0.39	0.29	77.6

[a] Data sources include forest inventory data on regional growing stock and removals obtained from the USDA Forest Service Forest Inventory and Analysis database; approximate regional land values, commodity prices, and wage rates; and hybrid MicroIMPLAN regional datafiles. The fundamental method used to derive factor shares is found in Marcouiller *et al.* (1996).
USDA, Forest Service. 1996. North central forest inventory and analysis database. Oracle database of county-level forest resource data for 101 counties in Lake States. Available at <http://www.srsfia.usfs.msstate.edu/scripts/ew.htm>
[b] Net of indirect business taxes.
[c] Calculated as the ratio of residual gross income (after payments to labor) to value of bare land plus value of growing stock.

income: low (less than $20,000), medium (between $20,000 and $40,000), and high (over $40,000). The balanced SAM equates regional receipts with respective regional expenditures.

Our initial fully balanced SAM is presented in table 2. Of particular interest is the introduction of the nonmarket assets (or public goods) created by the existence of the forest itself. Note that we model it as a fourth factor of production and under current design, it enters as a factor of production in the recreational industry (production sector 6: retail/services), but that it does not enter into timber production and services (production sector 2). The value of producing these public goods (derived through the opportunity cost approach) is tracked in the institutional row by tenancy group reading down the public-good factor of production column. As the SAM stands, it reflects a conservative estimate of nonmarket values.

The SAM shows that growing trees (timber production) and wood processing represented roughly 264 million dollars and 9.38 billion dollars, respectively, of total output in the Upper Great Lake States during 1993. These accounted for roughly 10 percent of the total 96.5 billion dollar gross product of the regional economy. Household income of the region was roughly 47 billion dollars. The total service and retail sector output accounted for about 25 billion dollars, of which, roughly 3.5 billion could be attributed to demand from out-of-region sources (tourism). Calculated using our opportunity cost approach, public goods from forest lands totaled roughly 80 million dollars during 1993.

A multitude of policy analyses is possible given the fully specified and balanced SAM. For the sake of brevity and as a means of illustrating the distributional consequences of forest policy impacts, a simple exogenous shock consisting of a 100 million dollar increase in public-goods output is applied to the SAM multiplier matrix as factor income.[3] This could be thought of as resulting from a shift in forest management to producing higher levels of nontimber benefits.

This increase in public goods could be accomplished in numerous ways. A naive way to justify this increase in public-goods production is to interpret it as a direct result of reducing the output of harvestable timber products (if translated directly into timber output, this total amount would represent a 38 percent decline over current output levels). To accomplish this assessment, one would be required to adjust timber output downward in a manner consistent with land use incompatibility. Currently, there are no models that would allow us to empiricize this trade-off. Also, even though this method would be consistent with the opportunity cost of producing public goods, it overlooks the ability to apply silvicultural treatments in a more sensitive manner.

[3] *Our model is endogenized through the set of household institutions, thus, interpretation of the impact assessment would include direct, indirect, and induced effects. A complete description of SAM analysis is beyond the scope of this paper. Interested readers are referred to Pyatt and Round (1985) or Holland and Wyeth (1993) for general discussion or to Marcouiller* et al. *(1995) for a discussion relative to timber production.*

Table 2.—*Environmental social accounting matrix for 101 counties within the forested portion of the Lake States (U.S.A.) (in MM of 1993 $)*

	Production Sectors								Factor Accounts			
	1	2	3	4	5	6	7	8	1	2	3	4
Production sectors												
1. Agricultural prod	224.3	9.5	58.7	1133.0	21.5	26.3	13.3	2.4				
2. Timber prod.and serv	57.1	20.8	0.7	0.3	171.4	0	0	0				
3. Manufacturing	195.0	19.4	4804.1	224.5	1093.3	1369.3	842.3	417.7				
4. Food/fiber process	13.3	5.9	11.7	975.8	2.1	261.3	0	9.1				
5 Wood processing.	11.1	.2	551.4	91.9	1087.2	30.2	1.1	4.6				
6. Retail/services	96.1	5.2	2779.9	233.3	673.2	1183.2	409.2	148.7				
7. F.I.R.E.	90.1	12.9	770.0	26.4	110.1	609.4	934.2	102.5				
8 Government	2.9	0.5	125.1	7.9	42.8	104.3	113.4	35.2				
Factor accounts												
1. Labor (total)	441.7	42.2	8091.7	579.8	2207.2	10717.7	1343.3	7084.6				
2. Capital	344.3	31.4	5339.8	521.4	1342.4	4683.6	3662.4	62.4				
3. Land	585.8	35.5	0	0	0	0	0	0				
4. Nonmarket Assets	0	0	0	0		77.6	0	0				
Institutions												
1. Timber Production												
a. National Forest									8.2	4.2	4.5	7.1
b. IPF									3.1	5.3	5.7	0
c. Other Public									11.9	6.1	6.6	27.5
d. NIPF									15.3	11.7	13.1	43.0
2. Commercial Recreation									1514.5	642.7	0	0
3. Wood Processing									1929.0	1151.1	0	0
4. All other									23125.3	11946.3	492.2	0
Households												
1. Low (<$20K)												
2. Medium ($20 – 40K)												
3. High (>$40K)												
Government												
Government revenue sources	40.7	4.0	620.0	31.3	159.1	1880.9	1390.0	15.9	3900.9	2220.5	99.1	0
Capital Savings												
Rest of world	1263.6	76.7	11099.8	1393.3	2473.5	4001.5	2229.1	576.9				
Total	3357.1	225.2	34252.9	5218.9	9383.8	24945.3	10938.3	8460.0	30408.3	15987.8	621.3	77.6

(*table 2 continued on next page*)

(*table 2 continued*)

	Institutions							Households						
	1a	1b	1c	1d	2	3	4	1 low	2 med	3 high	Government	Capital	Rest of world	Total
Production sectors														
1. Agricultural prod.								62.3	108.8	52.0	30.4	19.1	1595.5	3357.1
2. Timber prod. and serv.								2.7	7.2	4.3	0	2.6	6.1	264.2
3. Manufacturing								223.8	519.8	308.1	2147.7	5958.3	16129.6	34252.9
4. Food/fiber process								255.1	432.9	200.9	51.8	5.7	2993.3	5218.9
5. Wood processing								17.9	43.1	30.4	21.1	166.6	7327.0	9383.8
6. Retail/services								3470.5	7896.1	4212.3	710.2	359.0	2768.4	24945.3
7. F.I.R.E.								1050.3	2473.2	1433.9	247.0	34.7	3043.6	10938.3
8. Government								301.6	713.5	518.2	5945.0	0.9	548.7	8460.0
Factor accounts														
1. Labor (total)														30508.2
2. Capital														15987.8
3. Land														621.3
4. Nonmarket Assets														77.6
Institution														
1. Timber Production														
a. National Forest											0			24.0
b. IPF											0			14.1
c. Other Public											0			52.1
d. NIPF											0			92.8
2. Commercial Recreation											9.7			2157.2
3. Wood Processing											0			3080.2
4. All other											0			35563.8
Households														
1. Low (<$20K)	1.5	.9	3.2	5.7	133.3	190.3	2197.3				5614.4		700.7	8847.2
2. Medium ($20–40K)	9.4	5.5	20.3	36.1	840.0	1199.4	13848.7				3592.0		1863.7	21415.1
3. High (>$40K)	5.9	3.5	12.8	22.7	529.1	755.5	8723.2				1509.1		5093.0	16654.8
Government														
Government revenue sources								564.3	2663.2	3049.2			3239.3	19878.4
Capital Savings	7.1	3.8	27.5	43.0	175.0	312.2	3423.5	278.9	1313.8	1509.5				7094.2
Rest of world	0.2	0.5	-11.7	-14.9	479.7	622.7	7371.2	2619.8	5243.6	5336.0		547.3		45308.9
Total	24.0	14.1	52.1	92.8	2157.2	3080.2	35563.8	8847.2	21415.1	16654.8	19878.4	7094.2	45308.9	

Another approach to modeling this change would be to produce public goods using alternative management strategies that rely on uneven-aged selective silvicultural techniques, such as those practiced by the Menominee tribe in northern Wisconsin. Were we to manage forests for timber outputs in a less "aggressive," more sensitive manner, how would the increased levels of public goods translate to regional economic impacts? This is the question that is initially modeled in this paper. The results are presented in table 3.

Public goods are linked to the production of tourism activities (retail/services). These have important connections to finance, insurance, and real estate activities. As a result of increased output, these activities employ more labor and capital inputs. There are also benefits that accrue to the timber production regimes themselves as differentiated by institutions. Given the structure of the SAM, it is important to realize that these benefits are not accruing to landowners as market-based receipts but as public-goods assets. Finally, as shown in table 3, the distributive impacts resulting from public-goods production increases are disproportionately focused within the medium- and high-income households.

The strength of this approach to modeling the policy problems presented earlier is its comprehensive snapshot of the regional economy detailing timber production and its linkages to tourism. The empirical procedures for estimating the model are relatively straightforward. The drawback is the SAM's inability to deal with market influences in anything but fixed price terms. Price effects within a supply and demand framework are overlooked, thus leading to overestimates of quantity change. Furthermore, a SAM doesn't allow feedback linkages within a regional economic circular flow between the market for goods and services and the market for factors of production. Also, results suffer from the inability to differentiate market from nonmarket benefits.

A General Equilibrium Approach

Production within a SAM is limited to a Leontieff production form that characterizes output as resulting from the use of inputs in fixed technical coefficient terms given constant prices. A traditional SAM cannot mimic the flexible substitution among primary factors that characterizes management decisions. This model is unable to capture alternative rates of return to various production technologies. For example, the intensity of forest management, particularly the use of even-aged silvicultural practices, influences the rate of return to forest management practices. The development of fast-growing hybrid trees, the dramatic technological improvements made in harvesting equipment, and the technical progress of wood processing have focused on efficiency gains, namely through cost minimization and profit maximization of the firm. Furthermore, given scarce resources, steady to increasing demand for outputs, and technical progress in production, one would expect significant price effects for land, labor, capital, and growing stock. Thus, SAMs are limited in their ability to model regional economic structures from a neoclassical market perspective.

Although in its early stages, we have begun to extend the SAM into more price-flexible production forms utilizing CGE methods. There are many forms of CGE models that address similar core issues (e.g., Boyd 1984, Adams and Parmenter 1995, Piggott and Whalley 1991). For example, the small stylized general equilibrium model developed by Coxhead and Warr (1991) appears to provide a feasible framework. Developed to assess production technology differences between irrigated and unirrigated rice in the Philippines, these authors use a Johansen-type CGE model to assess three factor technology biases. To be adapted to the set of forest production problems outlined above, the Coxhead and Warr model can assess regional timber production that takes place under two management intensities characterized by fixed land resources, and which accordingly experience differential rates of silvicultural inputs even while facing the same prices for output and variable inputs. On the surface, this model would appear able to generate distributional results for several classes of households distinguished by their ownership of factors and by their patterns of consumption. Specifically, modeling components include complete specification of (1) factor demand

Table 3.—*Effect on regional households of a 100 million dollar increase in public-good output (101 counties in forested portion of Upper Great Lake States in millions of 1993 U.S. dollars)*

Account	Initial household income distribution		Fixed price impact	
	Million dollars	*Percent*	*Million dollars*	*Percent*
Households				
Low income	8,847	18.9	7.84	8.9
Medium income	21,415	45.6	49.44	55.9
High income	16,655	35.5	31.14	35.2
Total	46,917	100.0	88.42	100.0

and product supply, (2) factor supply, (3) household income and expenditures, and (4) price setting and market clearing.

Several significant empirical difficulties are evident in developing CGE models. Whereas SAMs provide empirical estimates of initial factor endowments, household consumption levels, and other benchmark data on the regional economy, there is a dearth of secondary data that allows us to easily parameterize a model. Chief among these parameters are elasticities of demand for factors with respect to factor and output prices, elasticities of supply for goods with respect to factor and own prices, and expenditure elasticities by household group. For timber production, Newman and Wear (1993) can provide a start for two landowership groups (industrial private forests (IPF) and nonindustrial private forests (NIPF)) and two product classes. Whereas gross sectoral parameters at the national level can be gleaned from other studies (e.g., Robinson *et al.* 1991), there is an inevitable need to estimate these for the Upper Midwest. This parameterization provides many avenues for future research.

DISCUSSION

As remote natural resource dependent regions explore alternative uses of their resources, the nonmarket value of those resources will play an increasingly important role in the local economy. Traditional economic models of regional structure completely miss the role of these public goods in the local economy. Using forest resources as an example, we suggest a simple and direct means for explicitly modeling nonmarket uses of these natural resources. Within our framework we identify a number of empirical issues that remain to be addressed. Our challenge then is to acknowledge the importance of non-market goods in the local economy and move towards building them into our analysis.

In terms of this particular effort, it should be considered midstream. We hope to better address the issues of local consumption and exports of the nonmarket goods resulting from alternative forest management regimes. Parameterization of the CGE model will entail significant work both identifying usable values from other studies and performing our own empirical estimates that are more region-specific. Our policy questions remain focused on regional economic consequences of alternative forest management regimes. Results of this work begin to provide us insights into the important questions that deal with how to best manage forests to attain both privately and societally determined demand for a wide array of goods and services.

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MODELING THE ECONOMY OF A TOURISM-ORIENTED, FOREST DEPENDENT REGION

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ABSTRACT. —This paper attempts to model the effects of environmental policies on a small, tourism-oriented, forest-dependent region. The interactions among economic activity, environmental quality, and tourism activity are examined by considering both environment and tourism endogenous. A two-sector computable general equilibrium model is developed and used to simulate the impact of environmental policies. We conducted simulation experiments under two scenarios: (A) environmental damage in the region is due to activity in the forest sector; and (B) activities from both forest and composite sector affect the local environment. Results indicate that an increase in environmental tax in the forest sector benefits the regional economy under scenario A. The converse holds true under scenario B. On the other hand, an increase in environmental tax in the composite sector hurts the regional economy under the assumption that environmental damage in the region is due to the activity in the forest sector and benefits the regional economy when environmental damage is assumed to occur from activities of both forest and composite sectors.

INTRODUCTION

In the recent past, concerns for the environment have prompted many researchers to model the economy-wide effects of environmental policies related to agriculture and other resource activities (Merrifield 1988, Bergman 1995, Tobey and Reinert 1991, Tsigas *et al.* 1996). However, very few studies have been conducted to model the impacts of environmental policies related to tourism activities. One of the reasons is that many people think of tourism as an industry that does not harm the environment (UNEP 1992). On the contrary, tourism is an industry with components including travel, accommodation and catering, leisure and entertainment, construction, manufacturing, food processing, and forest recreation (Peter 1990). Activities related to these components may have an impact on the environment.

Many researchers have investigated the effect of tourism on regional or national economies (Johanson and Moore 1993, Archer and Fletcher 1996, Adams and Parmenter 1995, Zhou *et al.* 1997, Lindberg and Johnson 1997). However, they did not consider that environmental quality would be affected by tourism activities and that changes in the environmental quality could in turn affect the tourism sector. In other words, earlier studies modeled tourism as an exogenous activity. Environmental impacts associated with tourism activities may alter the attractive features of the resource and thus influence the experiential quality of that resource from a user perspective. For example, when a wilderness lake becomes more accessible to users, it can no longer offer the same experience of distance and separation from human habitation (Farrell and Runyan 1991). Environmental damages and associated experiential degradation of a recreation resource may have a significant impact on the level of visitation, thereby affecting the overall economy of a region. This suggests that it is appropriate to consider tourism as an endogenous activity that may be responsive to a set of economic and environmental variables.

It is very well documented that activities related to resource sectors (agriculture, forestry, or mining) may cause damage to the environment. Therefore, public agencies often impose restrictions such as taxes on inputs or outputs, standards on management practices, and even preservation or closure of areas from production to control environmental damage. For example, the government of Alberta chose to restrict logging activity near the Rocky Mountain foothills because of environmental concerns. A proposed coal mine near Jasper National Park, Canada, has attracted much criticism from environmentalists. It was thought that the new mine would adversely affect wildlife habitat and thus alter the experiential quality of the national park. In the Pacific Northwest region of the United States, large tracts of

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forest areas are closed to logging activity to protect the habitat of the spotted owl. The arguments that intensive use of pesticides and fertilizers in agriculture causes ecological damage have led the U.S. government to undertake an acreage reduction program in the agricultural sector.

On the other hand, it is generally believed that tourism is a "green" sector that does not harm the environment. Tourism is also often characterized as an economic activity that employs relatively simple technologies, draws abundant domestic labor, requires limited capital investments, earns substantial net foreign exchange, and constrains industrial expansion and thus urbanization (Eadington and Redman 1991). As a result, it is not common to see protests against the expansion of activities related to the tourism sector. For example, restrictions on the number of visitors to a national park or on the development of recreational facilities in and around the park are not common. However, a close observation of any tourism-dependent region suggests that activities related to tourism impact the local environment. Rapid growth in tourism, for example, has caused an increase in forest fires and extinction of plant species in Mediterranean forests; led to more forest felling and forest fires in the Himalayas; and resulted in the damage of coral reefs in Kenya, Madagascar, and Seychelles (UNEP 1992). These environmental impacts of tourism, underestimated in the past, are now receiving attention. For example, Page *et al.* (1996) have noted that if visitor numbers and tourism development are allowed to continue, it will cause serious and irreversible harm to Banff National Park's ecological integrity and its value as a national park. Based on their recommendations, the Heritage Minister of the government of Canada announced a series of restrictions on the use of Banff National Park. These include establishing limits and reservation systems on the most popular hiking trails, eliminating all sport fishing, closing some hotels/campgrounds, and capping the permanent population of the town of Banff at 10,000. The following discussion suggests that regulations on tourism-related activities are required to ensure sustainable tourism development. Failure to incorporate the environmental impacts of tourism and the feedback effects on tourism in economic analysis may result in overestimating the role of tourism in regional economies.

This study attempts to provide a theoretical framework to model the interactions among economic activity, the environment, and tourism. First, the model incorporates linkages between the tourism sector and environmental damage and focuses on the implications for the regional economy. Second, the study considers two types of environmental damage functions: (1) it assumes that economic activity related to resource sectors affects the local environment; and (2) it considers that activities of both the resource and tourism sectors affect the environment. By conducting simulation experiments, the study shows that impacts of an environmental policy, such as an increase in an environmental tax, differ under these two types of environmental damage functions. The emphasis is placed on a tourism-oriented, resource-dependent region where the resource and tourism sectors compete for a scarce resource such as public land. Finally, the study points out a number of areas where future research is needed in extending and applying the model to a particular region.

The paper is organized as follows: the second section presents a general model of the economy of a resource-dependent region; the third section discusses the details of an operational model and data used in simulation experiments; the fourth section presents simulation results; finally, a brief summary is provided along with conclusions and suggestions for further research.

MODEL SPECIFICATION

The model is kept as simple and general as possible so that emphasis can be made on the interactions between the economy and environment and their impact on tourism. A small regional economy with two productive sectors is considered: the resource sector (R), which includes industries such as forestry, and the composite tourism sector (C). The resource sector is assumed to be a net exporter and a price taker in the international market. We assumed that all goods and services produced by the composite tourism sector are consumed in the domestic market and thus treated as a nontraded sector. Tourists from external regions who visit the region also consume these goods and services, but they do so within the regional market. This implies that a change in the number of visitors causes a shift in the demand for tourism goods and services in the region. The regional economy consists of two factors of production: a composite input consisting of labor and capital (L); and land (D). It is assumed that both inputs are used in each sector and mobile across sectors. Furthermore, it is considered that all factor endowments are fully employed between the two sectors. For the sake of simplicity, labor mobility across regions is ignored.

Production Functions of the Economy

The first and second parts of equation (1) define, respectively, the production of resource output and composite tourism output. It is assumed that production functions are well behaved and homogenous degree one.

(1) $R = R(L,D) \quad C = C(L,D)$

Factor Markets

Equations (2) and (3) show that factor inputs are fully employed between the two sectors of the region. Equation (4) indicates that factor proportions depend on relative changes in factor prices. With constant returns to scale, the product of α_{ij} and levels of output give total factor demands.

(2) $\alpha_{LR}R + \alpha_{LC}C = L$

(3) $\alpha_{DR}R + \alpha_{DC}C = D$

(4) $\alpha_{ij} = \alpha_{ij}(W,V)$

where α_{ij} = input i required to produce a unit of j; i = L,D; j = R, C; W = wage; and V = rental rate of land.

Zero Profit Conditions

Equations (5) and (6) show that the product of α_{ij} and factor prices give unit costs. Since the production functions are homogeneous degree one, the value of output must be exhausted once factors are paid. In other words, in a competitive equilibrium, unit costs equal market prices.

(5) $\alpha_{LR}W + \alpha_{DR}V = PR$

(6) $\alpha_{LC}W + \alpha_{DC}V = PC$

where P_i = unit price of i and i = R, C.

Environmental Damage

A conventional notion is that only activities related to resource sectors (such as logging, mining, and oil and gas extraction) cause significant damage to the local environment, while tourism does not affect the environment. However, as discussed in the introduction, the tourism sector may also cause significant damage to the environment. Therefore, two types of environmental damage functions are considered. First, it is assumed that land use and the level of output in the resource sector affects the environment. Second, it is considered that land use and the level of output in both sectors affect the environment.

(7) $E = E(\alpha_{DR},R) \quad E = E(\alpha_{DR},R,\alpha_{DC},C)$

where E = environmental damage.

For the sake of simplicity, the model does not consider the dynamics of environmental impacts. The ability of the environment to assimilate environmental damage may change over time. The assimilation rates may also vary with the nature of the impact.

Tourism Activity

Equation (8) defines tourism activity and contains two scenarios. In both cases, it is assumed that visitors are responsive to changes in the price of the composite tourism good. For example, the rise in airfares and hotel costs may cause a decrease in the number of visitors. Therefore, the price of tourism goods and services is included in both cases. With regard to environmental damage, it is expected that the level of tourism activity depends on the quality of the site, which is affected by activities related to producing sectors of the economy. For example, a decline in the water quality (for example, due to sludge disposal from a local pulp mill or soil erosion from logging activities) of the river systems may have a negative impact on sport fishing activity. Therefore, environmental damage is considered as one of the determinants of tourism activity. However, in the first part of equation (8), it is assumed that only the environmental damage associated with the resource sector's activity influences the level of tourism. In the second part, tourism is shown to depend on the environmental damage associated with the activities of both resource and tourism sectors.

(8) $T = T(E_R,P_C) \quad T = T(E_R,E_C,P_C)$

where T = tourist activity or tourists or visitors; E_i = environmental damage associated with the production of i; and i = R, C.

The changes in the environment in response to activities in the resource or tourism sectors may affect visitors differently because visitors have diverse objectives. For example, hunters may appreciate more clearcut areas while bird watchers and hikers may like to have old growth forests.[2] On the contrary, Bostedt and Mattsson (1995) have found that a decrease in the size and increase in the number of clearcuts has positive impacts on tourism. This suggests that the relationship between the changes in the environment and the number of visitors may be nonlinear. Those complex relationships are not considered in this modeling exercise and it is simply assumed that environmental damage would have a negative impact on tourism.

Demand for Goods and Services

Equation (9) shows that the demand for tourism goods and services arises from households within the region and outside visitors. Consistent with consumption and demand theory, both regional income (Y) and the price of the tourism good are included in the demand function.

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[2] *Peter Boxall, Canadian Forest Service. Edmonton, AB, Canada. Personal communication.*

(9) $C = C(Y, P_C, T)$

Regional Income

Equation (10) indicates that regional income equals the sum of the value of output in both producing sectors.

(10) $Y = (R P_R + C P_C)$

MODEL TRANSFORMATION

A convenient way of determining the comparative static effects of changes in exogenous variables is by transforming the general model into its proportional change form. The model requires relatively little data in its proportional change form and the results of comparative statics can be interpreted as elasticities. However, this format introduces linear approximation errors and thus is valid for only small changes in the exogenous variables. Since simulation experiments conducted later in this study deal with only 1 percent changes in exogenous variables, approximation errors are expected to be small (see Hertel *et al.* 1992 for details on linear approximation errors). Model transformation involves total differentiation, manipulation, and rearranging the equation of the system (see Johansen 1960 for details).[3]

Model transformation resulted in a system of eight equations with eleven variables (Y, P_c, P_R, R, C, W, D, E, T, L, and D). Since the number of variables was greater than the number of equations, L, D, and P_R variables were treated as exogenous. In solving the system of equations for changes in endogenous variables, we used a set of hypothetical values for parameters used in the model. In assigning values, we assumed that the resource sector was land intensive while the tourism sector was labor intensive. A Cobb-Douglas functional form was assumed for production and utility functions, and thus a unit value was assigned to the elasticities of substitution and the elasticities of demand for the tourism good. Similarly, we gave unit values for the elasticities of environmental damage with respect to each economic activity, and for tourism with respect to the environmental damage and the price of the tourism related good. One should be aware that model results may be sensitive to the parameter values chosen for simulation experiments. However, we thought that the use of the same set of parameters in both scenarios of environmental damage may not alter the general result of the analysis. We used GEMPACK 5.1 software to carry out the simulation experiments.

[3] *The details of model transformation can be obtained from the principal author upon request.*

SIMULATION RESULTS

One of the policy instruments governments have in regulating the activities of producing sectors is tax. For example, an imposition of an environmental tax per unit of output would cause an increase in the marginal cost of production and thus a decrease in the production of output. This study simulated the impact of a 1 percent environmental tax (Z_i, where i = R, C) in each of the sectors of the regional economy. In each case, the impacts are investigated under two scenarios. In the first case, environmental damage is assumed to occur from the activity of the resource sector (Resource-Environment (RE) Scenario). In the second, environmental damage depends on the activities of both the resource and composite tourism sectors (Integrated Tourism-Environment (ITE) Scenario). Table 1 reports the impacts of the tax in each of the producing sectors on several variables. The values are percentage changes with respect to a 1 percent change in the tax.

Columns 1 and 2 of table 1 show the impact of a 1 percent increase in environmental tax in the resource sector, under RE and ITE scenarios, respectively. Since the parameters used in the simulations are hypothetical, we will not focus on the absolute changes in these variables. Instead, we will emphasize the differences between the two scenarios. The results show that in both cases the output in the resource sector falls; the demand for the tourism good increases; and the returns to land decline. Nevertheless, the RE scenario experiences a larger increase in demand for tourism and larger declines in resource sector output and returns to land than the ITE scenario. These differences can be explained by focusing on the source of the environmental damage.

In the RE scenario, the reduction in the activity of the resource sector causes an improvement in the environment. The improvement in the environment has a positive effect on tourists in the region. Although the increase in the price of the tourism good discourages tourists, the results show that this effect is completely offset by the expansion in tourism associated with an improvement in the environment. Therefore, an overall increase in the number of visitors is produced. The results show that the expansion of the tourism sector, which leads to an increase in regional income, compensates for the decrease in the output of the resource sector. The stimulus for the tourism sector comes from two sources. First, with a contraction in the resource sector, some factors of production are shifted to the tourism sector. Since the tourism sector is assumed to be labor intensive, the increase in the tourism sector generates more demand for labor than the demand for land. Consequently, there will be an increase in the wage rate and a fall in the rental rate of land. Second, an improvement in the environment also stimulates tourism activity.

Table 1.—*Impact of 1 percent increase in environmental tax on each of the producing sectors (in percent changes)*

Variable	Tax in resource sector		Tax in tourism sector	
	RE Scenario[a]	ITE Scenario[b]	RE Scenario	ITE Scenario
Regional income (Y)	0.0137	-0.0021	-0.0530	0.0083
Price of composite (Pc)	0.0023	-0.0047	-0.0091	0.0183
Resource output (R)	-0.1022	-0.0058	0.3962	0.0226
Composite output (C)	0.0885	0.0051	-0.3433	-0.0196
Wage (W)	0.0120	-0.0043	-0.0671	-0.0038
Land rent (D)	-0.0291	-0.0066	0.0923	0.0053
Environmental damage (E)	-0.0796	0.0023	0.3086	-0.0088
Tourism (T)	0.0772	0.0025	-0.2994	-0.0095

RE = Resource-environment; ITE = Integrated Tourism-Environment.

[a] Environmental damage is assumed from the resource sector.
[b] Environmental damage is assumed from both the resource and composite tourism sectors.

In the ITE scenario, the effect of the tax in the resource sector is shown to have a negative effect on the environment. The improvement in the environment generated by the contraction of the resource sector is offset by the environmental damage associated with the expansion of the tourism sector. This may have a depressing effect on the number of visitors and thus on the demand for the tourism good. Furthermore, the expansion in the tourism sector is not shown to offset the contraction of the resource sector. Therefore, there is a decline in returns for factors of production and an overall reduction in the regional income. In sum, the results suggest that the tax policy in the resource sector benefits the regional economy under the RE scenario and hurts it in the ITE scenario.

We also conducted simulation experiments by imposing an environmental tax in the tourism sector. Again, the impact of the tax policy was investigated under the two scenarios as explained above. In the RE scenario, the environmental tax causes a significant decline in the tourism sector and an expansion in the resource sector. Unlike the case of the tax in the resource sector, the tax in the tourism sector causes a decline in the wage rate and an increase in the rental rate of land. The results also show that under the RE scenario, the expansion of a polluting sector, R, causes significant damage to the environment and therefore a reduction in tourism activity. Furthermore, the expansion in the resource sector is not shown to offset the contraction of the composite sector. As a result, we notice a decline in regional income. On the other hand, under scenario B, the impact of a tax in the composite sector actually improves the environment. This suggests that the improvement in the environment due to the contraction of the tourism sector offsets the damage associated with the expansion of the resource sector. Thus, an overall improvement in regional income is noticed. In sum, the results suggest that the tax policy in the tourism sector hurts the regional economy under the RE scenario but benefits it in the ITE scenario.

CONCLUSIONS

Recently, environmental impacts of tourism have been receiving more attention. However, very few studies have been conducted to model the interactions between tourism and environmental damage. This study provides a framework to model the interactions among economic activity, the environment, and tourism in the context of a tourism-oriented, resource-dependent region. In particular, the model considers both environmental damage and tourism as endogenous variables. We investigated interactions under two types of assumptions about environmental damage. First, it was assumed that environmental damage in the region is largely due to the activity related to the resource sector. Second, it was considered that activities from both the resource sector and the tourism sector affect the local environment. Using a simple computable general equilibrium model and conducting simulation experiments, we showed that the effect of a policy change differs under these two assumptions. The results indicate that an increase in an environmental tax in the resource sector benefits the regional economy if one assumes that environmental damage only comes from the resource sector activity. The converse holds under the assumption that damage to the environment occurs from both resource and tourism sector activities. On the other hand, while an increase in an environmental tax in the tourism sector hurts the regional economy under the first assumption, the tax policy benefits the regional economy under the second assumption. These findings have important implications for sustainable tourism management decisions.

The model developed in this study is simple and very general in nature. Depending upon the region, time frame, and issue under investigation, several extensions can be made:

1. The regional economy can be disaggregated into more sectors and factors of production. For example, the composite tourism sector can be subdivided into recreation, manufacturing, and the service sector. Resource sectors can also be disaggregated into forestry, mining, oil and gas, and agriculture. Similarly, combined labor inputs can be disaggregated into labor and capital. Labor can be divided into skilled and unskilled labor. The mobility of unskilled and skilled labor across sectors varies.

2. Depending on the short-run or long-run scenario, factor markets can be modeled under different scenarios. For example, capital can be sector specific in the short run, but it is mobile across sectors in the long run. In the very long run, capital can be mobile across the regional boundaries. Therefore, in the very long run, issues such as international migration and foreign flow of capital may have to be considered.

3. If the resource-dependent region has market power in the international market for its exports, it is appropriate to consider the price of the resource sector endogenous. For example, in modeling the economy of British Columbia, several researchers have considered the price of the wood products sector as endogenous (Percy 1986).

4. A variety of flexible functional forms can be used to specify production technology, household preferences, and environmental damage. They include Constant Elasticity of Substitution (CES), Constant Ratio of Elasticity of Substitution Homothetic (CRESH), Generalized Leontief, and Translog functions.

5. Savings, investment, trade balance, and various types of social accounts can be included in the model along with the government sector. In some cases it may be appropriate to model these issues in a dynamic setting. GEMPACK 5.1 or MPSGE/GAMS software are now available to handle dynamic analysis.

6. Modeling environmental damage and tourism activity requires input from various disciplines. For example, information on marginal damage to the environment due to additional logging, mining, or oil drilling have to be obtained from experts in those areas. Modeling marginal emissions from various production activities, pollution assimilation rates, and threshold limits of the environment involves interdisciplinary research. Furthermore, issues such as an increase in the probability of forest fire associated with visitors and extent of damage under alternate production activities can also be incorporated in extended models.

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THE COMMUNITY OPTIONS MODEL©: OUTCOME PROJECTION FOR COMMUNITY DEVELOPMENT DECISIONS

Daniel R. Talhelm and Aarne H. Frobom, Jr.[1]

ABSTRACT.—The Community Options Model for Transportation-Related Issues (COMTRI) is designed to help the Michigan Department of Transportation (MDOT) and rural communities "see" the impacts of choices they must make. It predicts change in indicators over time—such as population, employment, income, government revenue and spending, property values, congestion, and community services—in response to policy or action scenarios posed by the user. COMTRI is a hybrid of knowledge-based and statistics-based systems analyses of community social, economic, and transportation systems, and their responses to events, actions, and policies. Experts and practitioners initially specified its structure. Then its 400 predictive equations were fitted to 1980-1992 data from three communities.

INTRODUCTION: SOCIOECONOMIC IMPACT ASSESSMENT IN DECISION MAKING

This project began as a response to highway improvement projects in Michigan. The Michigan Department of Transportation (MDOT) needed better forecasts of the impacts of alternative improvement schemes on communities. Projects included relocations of State highways bypassing main streets, freeway extensions, widening of main streets, and one-way pairs. Staff needed to choose between proposed alternatives, to forecast project impacts for National Environmental Policy Act (NEPA) reporting, and to respond to local controversy over the proposals.

People want to receive the most benefit per unit of cost, considering all benefits, costs, and related impacts, both direct and indirect. However, even in clearly beneficial projects, certain groups may bear more costs than benefits. Public debate over impacts often focuses on highly visible or notorious issues such as the adverse impacts on long-established downtown retailers—pillars of the community—when traffic is relocated to a new route or competing destinations are made effectively "closer" by a new road. They want to know how proposed alternatives will impact their neighborhoods or businesses, how they can best manage adverse changes, and how to take advantage of new economic opportunities.

Socioeconomic (or social) impact assessments are intended to provide most of the information needed to evaluate such choices from the public point of view. Assessments of the State/national, community, and community-segment perspectives should form the heart of agency and public debate regarding which road projects should be undertaken. Thorough analyses of alternatives may also suggest which other actions and policies are also needed to cope with and take advantage of the prospective changes.

However, impact assessments are rarely actually used this way. They are almost never used to help formulate the best actions or project options. Economic and social information is expensive and not readily available, and is used too infrequently to be understood by the general public. Impact assessments are more likely used to support decisions that have already been at least tentatively decided.

Socioeconomic impact assessments have been so intractable because our standard approaches to modeling economic and social systems have been unable to disaggregate the complex simultaneous systems involved even in small communities. General models fail to explain individual differences between communities. For instance, regional land use allocation models have been used for some time in conjunction with regional transportation system models. Econometric and input-output

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models are being used to test the economic worth of very large-scale road system changes, such as new multi-State freeways. However, such models are inaccurate at the community level and estimate only some of the variables needed for community impact assessments.

Case studies have instead formed the backbone of forecasting local impacts, especially impacts on retail, residential, and other land development. Observations of past impacts of small-town bypasses, for example, now number in the hundreds, enough to provide a basis for statistical study. However, the same problem arises: even a large number of cases is insufficient to statistically estimate all of the factors that influence the outcomes in any individual instance.

Modeling Approach

Our approach to this problem was to combine case study data with existing scientific and practical expertise on community economic and social relationships, and, using current modeling technology, create an intelligent tool for estimating such impacts. Our tool—the Community Options Model for Transportation-Related Issues (COMTRI)—is designed to estimate the social and economic impacts of highway realignments on rural Michigan communities for MDOT as well as to permit users to explore the impacts of countless other community development options.

COMTRI allows MDOT and individual communities to quickly "see" the likely outcomes of potential highway realignments and other social and economic changes, and of potential community responses to such changes. It predicts the change in community *indicators* over time—such as population, employment by sector, income, unemployment, tax rates, local government income and spending, property values, vehicle trips and congestion, educational attainment, and community services quality—in response to policy or action scenarios posed by the user.

COMTRI differs in two major ways from most current models. First, it combines elements of both expert systems and statistical approaches. A group of experts specified a model far more complex than could be estimated with any purely statistical approach (within practical limits), yet each relevant equation was fitted to actual time-series data from three test communities. It also includes several qualitative variables that are described below. Second, COMTRI views time, equilibria, and space from an unusual perspective for an economic and social model: it uses the recursive, nonequilibrium, spatially oriented approach often used in forestry and ecological models. COMTRI was written in STELLA II®, in which interdependencies are handled by feedback loops with timing delays and iterations, rather than simultaneous equations. Users specify the number and frequency of iterations. (COMTRI cycles quarterly for 16 years.) Vehicle flows, retail/wholesale sector activity, tax rates, and commuting to work all vary spatially as well.

Economists classically view behavior from an equilibrium perspective. Equations simultaneously explain static equilibria, aggregating transactions over some often-unspecified time period in a spaceless world. Even time-series analyses aggregate behavior within observation periods such as years or quarters. Ecologists tend to view phenomena fundamentally differently (Brockstael 1996): as a recursive series of individual interactions over time and space. Ecologists' recursive models may or may not reach equilibria. Simultaneous models are rare. Forestry models are generally similar to ecological models, but usually involve longer time periods. Spatial phenomena are central to ecological and forestry models, but are generally limited in economics to models of land and recreation site values. Finally, forest and ecology models often consider in detail the forest/ecology consequences of human disturbance, but ignore most subsequent interactions with society, whereas COMTRI does the reverse, considering only the social consequences of many natural or human disturbances. By linking COMTRI with ecology models, it should be possible to create more complete, "ecosystem approach" models of human/environmental interactions.

The rest of this paper describes COMTRI and its development. The following section illustrates the nature of COMTRI and its use as an interactive decision support system by MDOT and Michigan's rural communities. It also demonstrates how decisions made by the community before and after the realignment can change the impacts of the realignment. Then we describe how the model's framework was specified by a multidisciplinary group of experts and practitioners, and its equations were fitted to data from three case study communities. We conclude that COMTRI's rapid and comprehensive impact estimates could be used as a decision support system. By exploring a variety of options, the agency and communities can identify strategies that are more likely to produce the outcomes they prefer. Skillfully used, such information can help unify community efforts to cope with and take advantage of highway realignments.

COMPARING OUTCOMES FOR TRANSPORTATION AND COMMUNITY OPTIONS: COMTRI AS A DECISION SUPPORT SYSTEM

Each community is unique. To depict a specific community, COMTRI must be initialized with data describing local conditions. Then it predicts *changes* in those conditions over time under any given scenario for the

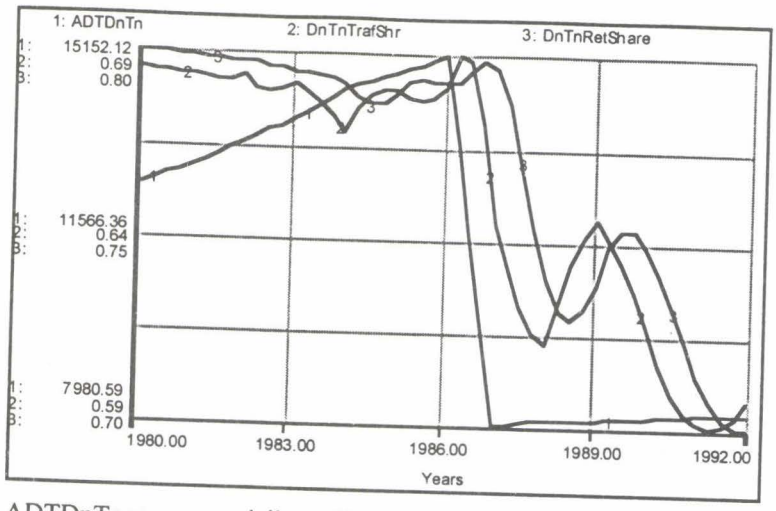
future. Therefore, initialization creates a unique model specific to that community. The major types of initial data are similar to those typically assembled in the environmental-scan phase of community strategic planning and include qualitative self-ratings by community members as well as statistical data:

Type of data	Source
Current population by age	Census, MI Dept Management and Budget
Current employment and earnings by sector	Bureau of Economic Analysis (BEA)
Current property values	State Equalized Value (SEV)
Current housing and occupancy, recent construction	Census, building permits
Community street/highway system schematic of primary routes	Mapping guidelines provided
Traffic flow patterns and related data	MDOT
[Optional: Earnings per worker projections	derive from BEA]
Transfer payments projections	derive from BEA
Current and expected competitive position and economic conditions	guidelines provided
Current and expected public budget allocations	Local Development Finance Authorities (LDFAs), Downtown Development Authorities (DDAs), etc.
Current and expected school funding allocations	
Self-assessment of quality-of-life indicators	guidelines provided

The process of assembling these data in itself can provide useful insight for community members, and may help them understand the model's workings and gain confidence in its results. It may also help prevent the public involvement process from involving only persons with specific complaints about a project. We hope the model will help limit undue focus on relatively small but highly visible impacts such as on a block of bypassed businesses or a neighborhood subjected to increased traffic or detours. Such issues must be considered, but undue focus can prevent due consideration of much larger community-wide benefits and costs.

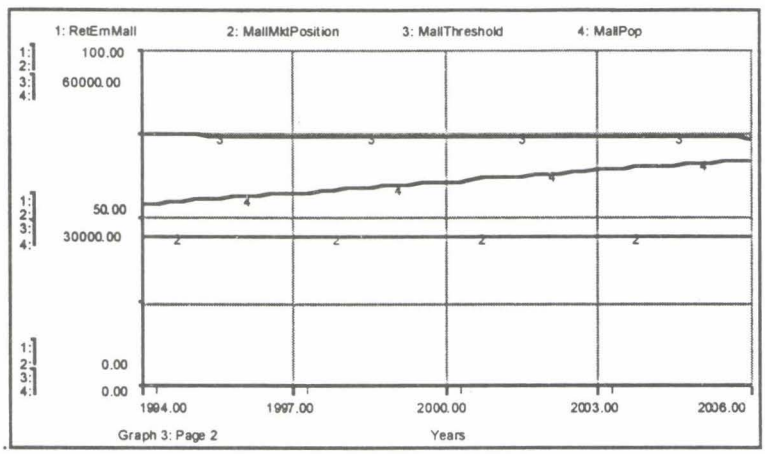
Figure 1 illustrates some impacts of a highway realignment (freeway bypass) completed in early 1987 in Reed City, MI, one of our three case study communities. Bypasses tend to redistribute retail sector activity from former thoroughfares to new bypass intersections. Average daily traffic on the downtown corridor (Variable 1, ADTDnTn) drops in 1987, followed by the downtown corridor's volume of traffic relative to that in other districts (Variable 2, DnTnTrafShr), and by the downtown business district's share of retail activity (DnTnRetShare). COMTRI predicts retail employment in each of five designated business districts as a function of traffic volume and other factors. Retail employment in turn influences traffic volume.

COMTRI predicts "mall" or outlying retail development independently of other retail activity. Mall development depends on a rule of thumb employed by developers, community policies toward mall development, and the influences of competitors. Development is assumed most likely at new intersections created by the bypass. The rule of thumb is that development is not feasible unless the potential market (MallPop in fig. 2)—the population within a 15-minute drive (AreaPop) plus 1.5 times average daily traffic (ADTDnTn), adjusted for competition—exceeds a threshold of 45,000 (MallThreshold). The adjustment for competition assumes that people use the closest retail anchor stores, so all residents of the 15-minute zone closer to a competing anchor store are subtracted from AreaPop. Any subtraction is also modified by the size of the competing malls or stores: larger competitors reduce AreaPop more. Rather than being fixed at 45,000, MallThreshold is a moving target. It is influenced by community ability to accomplish goals (an index called CommCompetence), zoning laws (MallAntiZoning), and the availability of water and sewer lines to the mall site (MallWatSewer). According to practitioners, zoning laws and water and sewer restrictions can delay, but not stop, mall development. In COMTRI, these restrictions raise or lower the mall development threshold. Figure 2 illustrates COMTRI's baseline prediction for Reed City, in which MallPop does not reach MallThreshold by the year 2006, so retail employment at malls (RetEmMall) remains zero. Figure 3 illustrates Scenario 1, in which one of the competing anchor stores moves away and is not replaced, opening the market to mall development in Reed City. MallPop



ADTDnTn = average daily traffic on the downtown corridor, DnTnTrafShr = downtown traffic volume relative to that of other districts, DnTnRetShare = downtown business district's share of retail activity.

Figure 1.—*Impacts of a freeway bypass completed in early 1987 in Reed City, MI.*

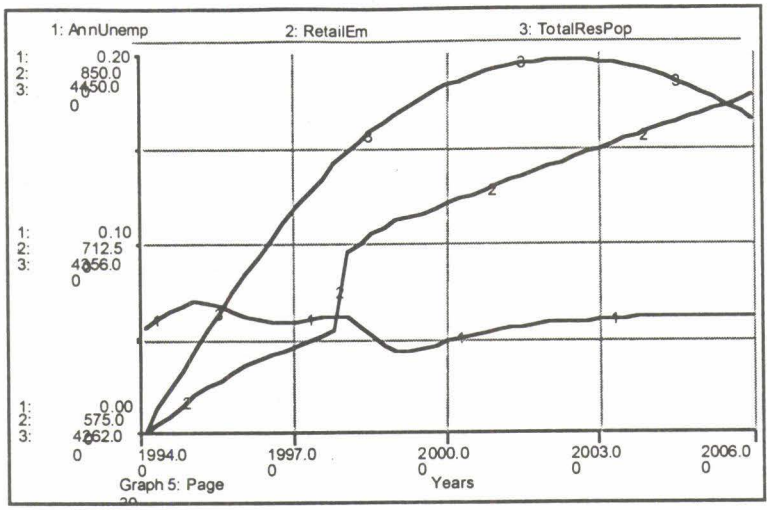


RetEmMall = retail employment at malls, MallMktPosition = adjustment for competition, MallThreshold = minimum population needed for a mall, MallPop = potential market

Figure 2.—*COMTRI's baseline prediction for "mall" or outlying development in Reed City.*

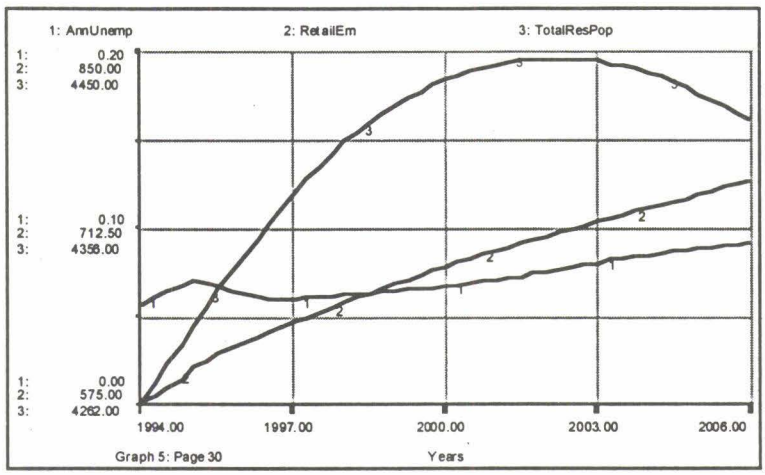
crosses MallThreshold, and mall employment begins soon after. By comparing baseline projections of indicators—such as the community's annual unemployment rate (AnnUnemp), total retail and wholesale sector employment (RetailEm) and resident population (TotalResPop)—to their levels under each scenario, users can evaluate the impacts of specific actions or conditions affecting the community (figs. 4 and 5).

In Scenario 2, suppose the fictional Plaid Owl near Reed City is discovered in 1997 to be endangered, causing forest harvesting to be permanently curtailed in 1998 (figs. 6 and 7). Employment in Reed City's agriculture/forestry/fisheries sector is actually almost entirely in agriculture, but here we assume that the number of acres in active agriculture and forest use drops by 8,000, or nearly half (Variable 2, AgForLU in figure 6), reducing employment in the sector from about 70 to about 45 (AgForEm). Suppose further, Scenario 2 continues, that in the year 2000 the forest is opened to bird watchers and the natural resource-based recreational attractiveness in the vicinity (Variable 3, RegionlRecAttrns) over a 3-year period increases from the 40th percentile among Michigan communities to about the 70th percentile. Consequently, total retail/wholesale employment (RetailEm) begins recovering after 2001 from its slightly reduced growth in 1999-2001, and by 2006 is above its baseline level. The unemployment rate jumps from 1999 to 2001



AnnUnemp = community annual unemployment rate, RetailEm = total retail and wholesale sector employment, ToResPop = resident population.

Figure 3.—*Mall development under scenario 1: loss of competing store.*



AnnUnemp = community annual unemployment rate, RetailEm = total retail and wholesale sector employment, ToResPop = resident population.

Figure 4.—*Baseline projection of unemploy ment rate, retail employment and population.*

(fig. 7), but then levels off, and by 2004 is below the baseline level. Total population follows a similar pattern. By examining up to about 400 other variables via similar graphs and tables, users can detect other impacts of the scenario. For example, they can see that by 2006 residential property values increase by about 0.5 percent, the number of seasonal homes increases by about 3 percent (one home in this case), the cumulative aggregate local government budget deficit increases from $60,000 to $230,000, and the amount of time required to drive through downtown during peak traffic increases from 3.6 to 3.8 minutes due to vehicle congestion.

COMTRI is intended for use by MDOT to improve its formal socioeconomic impact assessments. It should increase their accuracy, comprehensiveness, and speed, and thus their usefulness in decision-making. Even the nature of the assessments will change, since COMTRI will force users to consider how the impacts of a given project may vary with the community's response to the change. MDOT will be able to estimate a range of impacts associated with various possible community actions or other conditions, rather than just one set of impacts.

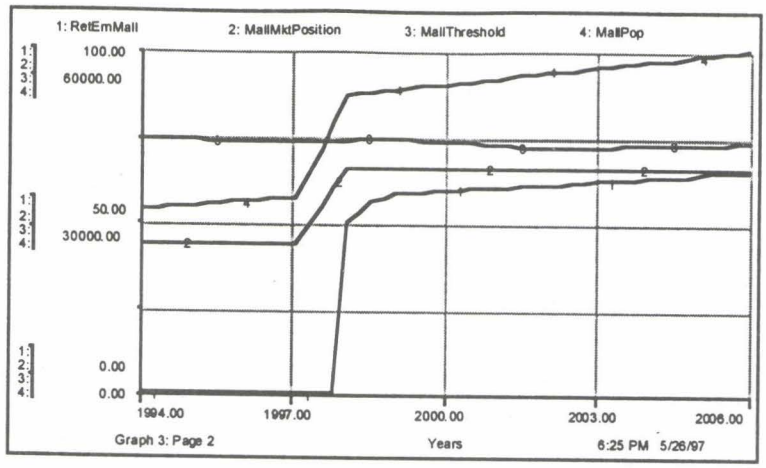


Figure 5.—*Unemployment, retail employment and population in scenario 1.*

RetEmMall = retail employment at malls, MallMktPosition = adjustment for competition, MallThreshold = minimum population needed for a mall, MallPop = potential market

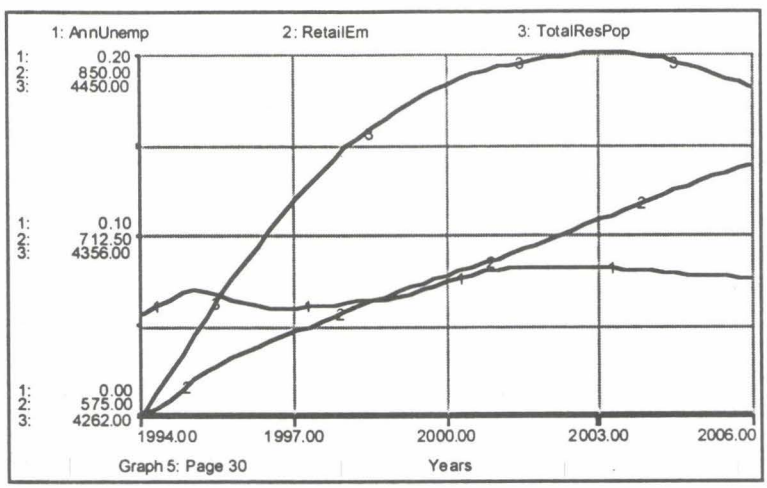


Figure 6.—*Unemployment rate, retail/ wholesale employment and total population under scenario 2.*

AnnUnemp = community annual unemployment rate, RetailEm = total retail and wholesale sector employment, ToResPop = resident population.

COMTRI was also designed in part to address the often-intense public interest in the outcomes of highway improvements. Our intent is to integrate it into the project-development process, helping simultaneously to predict impacts and inform debate. We believe this information can provide a common ground for resolving competing interests and views within an agency or a community.

COMTRI can be equally useful to local governments, planning commissions, consultants, or advisory agents such as Cooperative Extension field staff. Communities can use the model as an alternative to State impact assessments or hired consultants, although it may not provide sufficient resolution of market potential for some local investment decisions. The many outputs from the model can enable a community to see all the major impacts (or the lack thereof) of a highway project at once.

COMTRI can also provide a wide range of decision support for community development and growth management. By exploring a variety of options, communities can identify specific tactics or broad strategies that are more likely to produce the outcomes they prefer. Outcomes can be evaluated under optimistic and pessimistic future economic conditions, with or without a variety of possible coping or follow-up tactics, or under a variety of broad, strategic planning scenarios. Skillfully used, such information can help unify community efforts, which should increase the community's chances of reaching its goals.

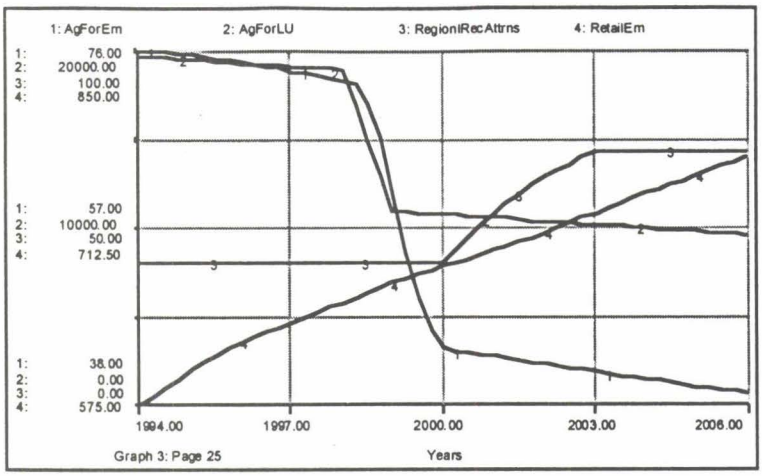


Figure 7.—*Scenario 2 assumes a reduction in agriculture/forest land use and an increase in the attractiveness of the area for recreation.*

AgForEm = employment in the agriculture/forestry/fisheries sector, AgForLU = land use within that sector, Region/RecAttrns = natural-resource-based recreational attractiveness, RetailEm = total retail and wholesale sector employment

We are currently evaluating the ability of Michigan State University (MSU) Extension field agents to use the model to facilitate a variety of regular and special community-development decision-making processes. For example, they might use it to help the city council or planning commission evaluate the outcomes of proposed projects or prospective openings or closings of large employers.

INTEGRATING EXPERT KNOWLEDGE AND STATISTICAL DATA

COMTRI is a hybrid of knowledge-based and statistics-based systems analyses of community social, economic, and transportation systems. Knowledge-based simulation models are simple forms of artificial intelligence, in which the model's equations mimic the thinking of experts on the topic. As in this instance, such models can utilize available human knowledge to specify relationships that would be impractical to estimate statistically. First, COMTRI's knowledge-based structure and many of its key equations were specified in general form by a group of experts and practitioners. After the workshop, roughly 400 of its approximately 800 equations were estimated by fitting equations to data from three case study communities over the period 1980-1992. The remaining 400 equations are constants or simple logical or mathematical operations such as summation that did not require fitting. The resulting model "thinks" much as the team would, but with equations grounded in statistical analysis. The remainder of this section describes both procedures in more detail.

Expert-Based Framework for COMTRI

COMTRI began with a workshop on transportation and community development in April 1993. The workshop followed a procedure largely based on the Adaptive Environmental Assessment workshop technique (Holling 1978, Walters 1986). The object of the workshop was to specify which components to incorporate into COMTRI, and their general interrelationships. The 21 participants included academic researchers in economics, sociology, and demography, several transportation engineers, and several community development practitioners, including State, regional, and local planners and community development specialists, two city managers, a city assessor, a township supervisor, and a city administrative assistant.

The workshop first listed current issues facing rural Michigan communities undergoing major highway realignments. Communities were defined as any population under 10,000 that identifies with and frequents a central rural location, and the cities, villages, and/or townships they inhabit. In view of these issues, the workshop listed the indicators and actions we wanted the model to predict and simulate. Indicators are the kinds of information people use to keep track of conditions over time. The objective of the computer model specified by the workshop is to predict changes in the indicators over time. Actions are the changes or options that are to be evaluated by the model. Some actions are policy changes or components that can be implemented by MDOT or by the community, such as highway realignment, park

development, or creating a Downtown Development (tax capture) Authority. Other actions may be natural or other exogenous events outside the control of the community, such as changes in State economic conditions or industrial relocations. Almost all of the following actions were eventually included in COMTRI:

Actions
Transportation options:
  Bypasses (freeway, limited access, highway access)
  Improvement (widen, controls, straighten, one-way pair)
Highway access controls: Curb cuts, boulevard versus five-lane
Controlling water/sewer hookups
Zoning extent and intensity
Master planning; Corridor planning
Community strategic planning
Economic development activity (EDA, DDA, EDC...)
Tax abatements
Change tax rates (millage, income tax rates)
Industrial parks; Business incubators
Permit planned unit developments
Airport development
Educate/train local work force
Intercommunity cooperation
Support services for elderly, etc.
Limit signs or noise
Park development, scenic preservation, open space
Provide off-street parking; on-street parking
Increase pedestrian capacity
Public communication (attitude surveys, meetings, etc.)
Develop public and private campgrounds, marinas, etc.
Beautification programs; Adopt-a-community theme
Promotion
Local budget reallocations
Annexation/separation—401(5)'s (revenue sharing)
New State tax laws
State/national economic conditions
Local competitive position for retail, tourism, etc.

The indicators were grouped into sectors. Participant subgroups specified which variables and general equation forms predict change over time in each indicator assigned to its sectors (see below):

Sector/indicator	Sector/indicator
Population	Labor Force/Commut./Households
Population by 7 age classes	Labor force and commuting
Population density index	Households
Senior attraction indexes	Property Values
Economy	Residential/developmental
Retail/wholesale	Commercial
Travel/tourism	Industrial
Construction	Agriculture/forest/open
Services/FIRE	Personal property
Manufacturing	Community Services/Indicators
Mining/transportation/utilities	Recreation/tourism
Education	Institutional services
Government	Community indicators
Agriculture/forestry/fisheries	Cost of living
Earnings	Cost of government
Economic base	Crime
Transfer payments	Housing
Personal income	Education attainment
Economic attractiveness	Social services
Retail Land Use	Public Budget
Retail and traffic by business district	City and township taxes
Traffic Volume and Safety	Education taxes and budget
Volume by road link	City/village/twp. revenue
Local trip generation	City/village/twp expenditures
Corridor volume/speed	County health/welfare/judicial
Traffic safety indexes	Fiscal equity
Seasonal Population and Lodging	Community Organization
Lodging	Self investment
Camping	Competence index
Seasonal homes	Attractiveness index

For instance, the economics subgroup specified variations of standard economic frameworks for predicting earnings and employment by sector in the community. They said that employment and earnings in the services, construction, and local retail sectors depend largely upon total community personal income. They also stated that employment and earnings in the retail mall sector depend in part upon the amount of income derived from outside the community (i.e., economic base), while employment and earnings in manufacturing and several other sectors depend largely upon state and national trends and decisions. Other equations were based on engineering approaches, practitioners, and trades' explicit and implicit rules of thumb, or group best judgment. Best judgment was used primarily to determine which variables to include in the model, and to specify general system and component interrelationships, rather than to detail specific relationships.

Equation Estimation

After the workshop, we began estimating the approximately 800 individual equations that comprise the simulation model. The equations are grouped into 11 sectors and 47 subsectors. Roughly half of the equations perform "housekeeping" operations, such as integration, summation, or recording constants, so they did not require statistical estimation or verification. The other half, representing real-world phenomena, were estimated or verified using data from Michigan communities.

Most equation forms were specified in the workshop, and simply needed to be fitted to actual data. We fitted equations to 1980-1992 data from three rural Michigan communities for which through traffic had been rerouted away from the downtown areas during the mid-1980's. We initialized the model to each community for 1980, then compared predictions to actual data from the community for 12 years: 1981-1992. Each equation was modified first to accurately predict conditions in one community, then two, and eventually all three communities simultaneously. In effect, each equation was fitted "manually" to data from the three communities. Usually we had to fit several equations operating in tandem, so rather than using a least-squares measure of fit, we considered the percentage error of prediction, the degree to which the equations influenced predictions of other parts of the model, and the degree to which the equations conformed to the model outline provided by the workshop.

For example, the final equations were able to predict the 1990 total population of each community within about 3 percent, given the communities' 1980 population and full knowledge of unemployment rates for the entire period. COMTRI estimates the population of each age class separately, and it predicted the population of each age class for each community within about 12 percent, except the 18- to 24-year-old age class in one community was overestimated by 21 percent. The communities' experiences in the period ranged widely, so we have reason to believe that the fitted equations will also predict well for other Michigan communities. The population of one of the communities, Reed City in northern Lower Michigan, grew by nearly 6 percent during the period, while its unemployment rate remained below the state average. Another, Manistique in the Upper Peninsula, lost about 5 percent of its population while unemployment was higher than the State average, whereas the third, Lapeer in southeastern Michigan, grew by over 7 percent in population while experiencing below-average unemployment rates through 1985, then above-average. Commuting patterns also changed sharply in Lapeer during this period for residents employed outside of the community and for nonresidents employed in the community.

It was necessary to consider more than simple statistical fit in specifying our equations because "everything is connected to everything else" both in the real world and in the model. Variables in the model are generally interdependent (co-determinant) rather than dependent or independent as assumed in statistical estimation. For instance, local population migration depends in part on local unemployment rates relative to surrounding unemployment rates; local unemployment rates depend in part on local migration (labor force size) and commuting patterns; and commuting patterns depend upon the distribution of job openings. We generally had to fit several co-determinant (but nonsimultaneous) equations simultaneously rather than one at a time. The computer programming software, STELLA II, does not solve simultaneous equations, but uses recursive feedback loops instead.

The workshop did not specify some equations needed in the model. In such cases, we generally asked practitioners or academic experts to help specify them, and then we followed the above equation fitting process. However, no one could definitively explain rural community-level population migration and school funding decisions, so we tested several possible explanations using data from communities statewide and regression analyses. For instance, we concluded that rural migration of high school graduates (18-24 age class) responds more to the difference between community and county unemployment rates than to absolute or relative State or national unemployment rates. Specifically, we rejected hypotheses that migration out of cities would increase migration of this age class to rural areas when State unemployment rates were high, and that rural residents of this age class migrate significantly to other States when local unemployment rates are much higher than national.

Data for several qualitative indicators and relationships were not available through normal statistical sources. In these cases, we asked community representatives to rate their communities on a percentile scale relative to other Michigan communities over the period. We assumed that these ratings were accurate and used them to estimate equations predicting change in indicator levels over time. We also asked community members to critique COMTRI results and forecasts, particularly considering these qualitative variables.

The road network in COMTRI is highly simplified, consisting of 10 nodes and links representing the major intersections and traffic flows. Through traffic forecasts are exogenous, but local auto and commercial traffic volumes are endogenous. Determining the percentages of through and local auto and commercial traffic utilizing each link specifies transportation alternatives.

Land use is also highly simplified. Only aggregate retail sector activity is predicted in each of five business districts. Each designated business district is associated with one or more road links. The retail sector is both influenced by and an influence on traffic volume on those links. Since COMTRI estimates employment by economic sector, number of households, housing units, commuting and similar variables, its ability to forecast land use could be expanded in the future.

As a final stage of model development, we are currently testing the model as a practical decision-support tool in three other rural Michigan communities for which new highway projects are proposed. Local MSU Extension staff and local officials are cooperating. Predictions that differ from expected outcomes will be reexamined and respecified if appropriate.

CONCLUSIONS

Simulation models are already providing effective, real-time decision support systems for some organizations. We believe COMTRI and other models will soon provide similar support for public agencies and communities. By exploring a variety of options, the agency and communities can identify tactics and strategies that are more likely to produce the outcomes they prefer. Skillfully used, such information can strengthen and help unify community efforts to cope with and take advantage of highway realignments.

COMTRI is also a great tool for learning about the economic and social dynamics and interrelationships of rural communities. Users and students will find that the model reflects the diverse expertise of experts and practitioners, data from case studies, and some original findings. Explorations can range from practical questions about options for managing their community's future, to academic questions such as the processes by which communities develop their own unique characteristics.

We recommend that community impact assessments recognize that impacts are jointly determined by the nature of the project/event and by the community's response to the change, and estimate a range of possible impacts associated with different scenarios instead of point estimates. Conventional impact assessment is supposedly a ceteris paribus process in which the proposed project is the only variable. However, ceteris paribus conditions are actually unknown. People respond to change, and these responses must be considered part of the consequences of the project. For instance, new gas stations and retail stores are generally one consequence of rural freeway interchanges—perhaps followed by housing, manufacturing, and/or other developments in the vicinity. The magnitude, timing, and mix of these developments depend upon future decisions by developers, local governments, competitors, and others. Some communities aggressively facilitate development, while others fight it. COMTRI makes it clear that such actions influence the impacts of the projects.

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IMPLEMENTING AN OBJECT-ORIENTED AND EVENT-CONTROLLED FOREST SUCCESSION MODEL[1]

Karl Hönninger and Manfred J. Lexer[2]

ABSTRACT.—The simulation environment for an object-oriented and event-controlled forest succession model is presented. An outline of the general architecture of the simulation environment and of the event-control is given. Subsequently the structure of a spatially explicit forest succession simulator developed and embedded in this simulation environment is described. For the construction of complex ecosystem models where an efficient utilization of hardware resources is essential, the presented tool proved to be a valuable alternative to other concepts.

INTRODUCTION AND OBJECTIVES

Based on the JABOWA/FORET concept (Botkin *et al.* 1972, Shugart 1984), a spatially explicit forest succession model for Austrian alpine conditions was developed. This model simulates radiation environment and regeneration in 3D-space based on a grid of 10 x 10 meter plots. From this it follows that we had to handle a complex model structure and had to meet high standards in processing performance. Thus, the simulator should meet the following requirements:

1. high processing speed and efficient utilization of hardware,
2. comfortable user interface for visualization and editing of the model, and
3. powerful interface to link model components.

To attain these goals, we decided not to employ a universal programming environment (e.g., C, FORTRAN) or an external simulation environment (e.g., Powersim). Instead, we developed a hybrid tool for the implementation of our succession simulator (Walther 1992). In this contribution, we describe the design of this tool with special emphasis on the event-control of the simulation model and the static system structure of the succession model.

DEVELOPMENT ENVIRONMENT

The simulator was implemented in C++. Powerful possibilities for dynamic storage administration as well as low-level commands enable an optimal utilization of computing power at reasonable cost. In addition, C++ provides tools for the development of comfortable graphical user interfaces and access to databases. To make the subsequent application of the succession simulator more user-friendly, we decided to separate source code for the pure administration of the model from the model logic itself. Thus, the development of the succession simulator was carried out at two different levels. Level 1 was the design of the hybrid programming-tool, which is essentially independent from the simulation model *per se* and will be called "simulation environment" throughout this paper. The simulation environment was needed for the programming and administration of the succession model and for the tying up of such a model in an EDP-system (Häuslein and Page 1995). Level 2 was the programming of the succession simulation model itself, the static model structure as well as the model behavior. Beside the general functions and programming aids of the employed programming language, all tools of our hybrid simulation environment (level 1) were available for this task.

Programming Approach

The choice of C++ facilitated an object-oriented (OOP) approach. We considered this approach ideal for the depiction of complex real systems (Kolstrom 1991). According to Balzert (1996) the concepts of OOP utilized for object-orientated simulation are:

1. An object combines data and operations (i.e., the properties of an object). Objects of the same type are

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represented by a class. This means that an object is an instance of a class. For each system, a class is defined whose variables correspond with the system attributes and whose operations characterize the system behavior.
2. Operations of objects are invoked by sending messages to them. The system behavior follows from executed operations.
3. Properties of classes may be inherited from a more general class. As an example, a class "conifers" can be derived from a class "trees".
4. Polymorphism means that a message sent to objects of a different class may invoke different operations of those objects.
5. Aggregation and associations define the relations between objects.

These concepts proved useful for the design of both level 1 and level 2. For the programming work on level 2 the object-oriented programming approach was slightly modified:

1. The event-control of the model is not carried out by messages which are addressed to a particular system. Instead, events are triggered which ultimately stimulate reactions in one or more systems.
2. If more than one instance of a system exists, at least one dimension is ascribed to each instance.
3. A system with more than one parent system is called an intersect system. Instances of intersect systems are generated by combining the instances of the individual systems.

Dynamic memory management was used to dynamically create instances of systems. This led to efficiencies in memory utilization and reduced the number of objects which had to be browsed during operation.

SIMULATION ENVIRONMENT

The simulation environment consists of two parts: a readily compiled application for the administration of the model structure as well as for the realization of simulation runs and an object-library in C++ for the programming of the simulation model. The application contains an interface to the object-library. The structure of this application is shown in figure 1.

The object "application" contains a graphical user interface for the development and administration of the succession model and the object "simulation". The object "simulation" encapsulates all essential modules for the storage of the model structure and the performance of simulation runs. The model base consists of a relational database and a collection of C++-source files. It serves as the base for the storage of the model structure. All model declarations are

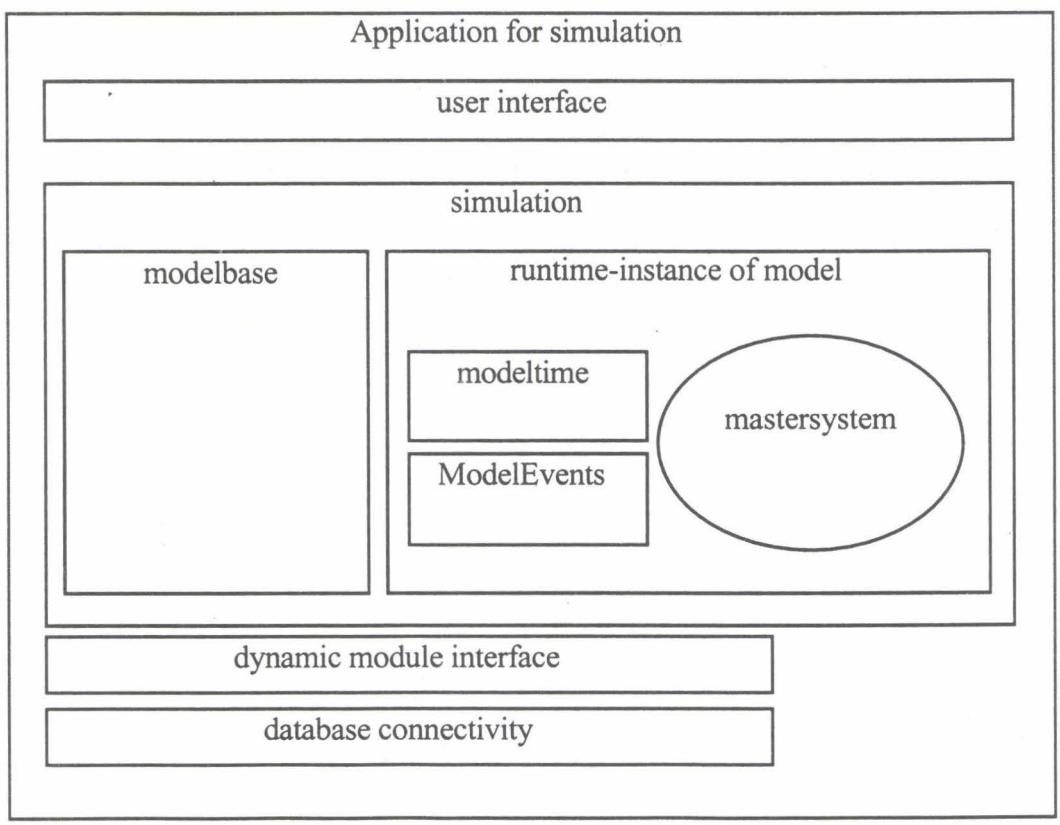

Figure 1.—*Structure of the simulation environment.*

stored in the relational database within the model base while model definitions are stored in C++-files. The linkage between the declarations and the definitions of model behavior is managed by the model base and can be visualized and edited with the graphical user interface integrated in the application. The model base architecture is object-oriented. The C++-files are used to generate dynamic link libraries (DLL) by utilizing the object "dynamic modules". Dynamic link libraries are executable files which are linked to the application during a simulation run. In addition to dynamic link libraries from the model base, DLLs of any source can be utilized. Input and output of simulation runs is stored in the "database" which can be of any format the user may choose. When a simulation run is started, the object "model" is generated as the runtime-instance of the succession model. Beside the systems of the model which are all integrated in the master system, their attributes and relations, the model-immanent time as well as a module for the event-control of events are parts of this object. The master system delimits the simulation model from its environment. It has the same architecture as the subordinate systems and is used as an "entrance" to the model structure.

EVENT-CONTROL

The event-control implies the model dynamics. Model dynamics include changes in model structure and in state of system attributes, which in turn are consequences of system behavior. System behavior is realized by different types of reactions, which are set off by events. Figure 2 depicts a schematic of the event-control mechanism.

Events

Three types of events are defined: TimeEvents, SimulationEvents, and SystemEvents.

TimeEvents are triggered through elapsing time. They are defined by the time of their first appearance and their repetition interval. When a model run is initialized, all TimeEvents are sorted by time of first appearance. As soon as invoked by the elapsing model time, each TimeEvent can cause the corresponding systems to react. The TimeEvent itself is then moved to a position on a list corresponding to its next appearance.

SimulationEvents provide information on the state of the model run for all systems of the model. The events Setup and ShutDown are especially important. Setup is called immediately after model initialization and before the model time begins to run and is relevant for systems which deserve a special initialization. ShutDown takes place when model time has run out or the simulation run had been stopped by external intervention. The effect of ShutDown is a reorganization of storage capacity.

For each system, SystemEvents can be defined. These system-specific events are either invoked explicitly by a system activity or involve a system attribute taking on a pre-defined value. Systems which react to SystemEvents must be subsystems of the current system. If several instances of such a system do exist, the corresponding SystemEvent will only be recognized by subsystems of the instance that set off the event.

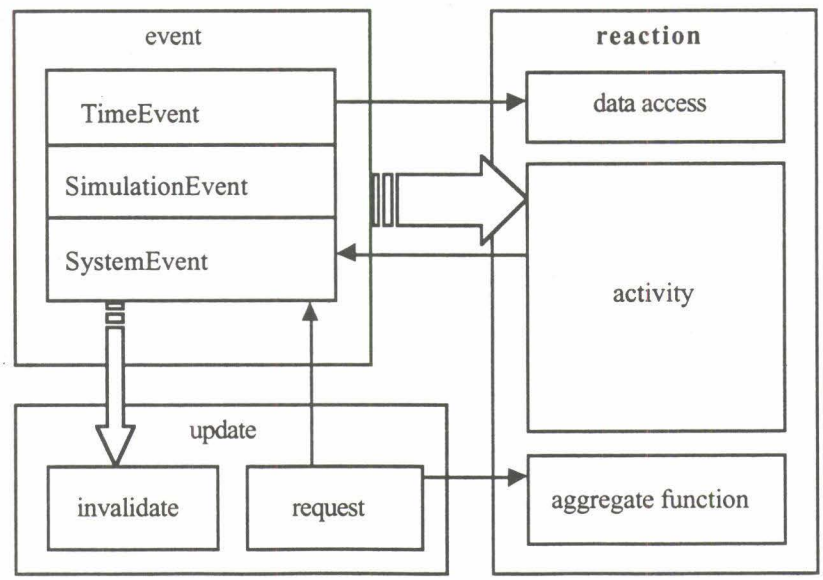

Figure 2.—*Representation of the event-control mechanism.*

Reactions

As a consequence of events reactions of systems or attributes evolve. A SystemActivity is a system-specific reaction on an arbitrary event. In course of the reaction, several attributes of the system or subordinate subsystems can be modified. Additionally, a SystemActivity can, by definition, trigger SystemEvents or create and delete subsystems. Thus, reactions bear the potential to change the state of system attributes and the model structure.

For some simple or frequently occurring reactions, it is not necessary to define a SystemActivity. Two possible alternatives exist: (i) Aggregating functions can be employed to scale up attributes of a subsystem with several instances to an attribute of the parent system, and/or (ii) To read values from a database, an automated database access can be used. Thereby all system attributes which are linked to a database query are actualized.

Update

Events can invoke the invalidation of object attributes. If invalid attributes are requested, the generation of "valid" attribute values is initialized. This process is managed by the module "update". If several attributes are requested at the same time, the sequence of these recalculations is implicitly defined by the interrelations between the attributes. In contrast to explicitly formulated recalculations, this concept provides greater flexibility in the maintenance and modification of the simulator.

STATIC SYSTEM STRUCTURE OF THE SUCCESSION MODEL

One major difference of our model in contrast to conventional forest succession simulators is the 3-dimensional spatial model structure. In this section we describe the static system structure of this model (fig. 3). The master system of our model is the system "Environment". It represents precipitation, temperature, and radiation above the canopy. The only subsystem of "Environment" is the system "Stand". Subsystems of "Stand" are "Plot" and "Canopy layer". "Plot" contains the characteristics of a small 10 x 10 meter patch of forest (position in the forest, site and soil properties). A "Canopy layer" is a horizontal slice of 5 meters width through the forest. The potential availability of a particular tree species on a particular plot in the forest is a realization of the seed production on all plots and of the seed distribution. This potential species availability is characterized by the system "Species potential".

The dimensions of model systems are described in table 1.

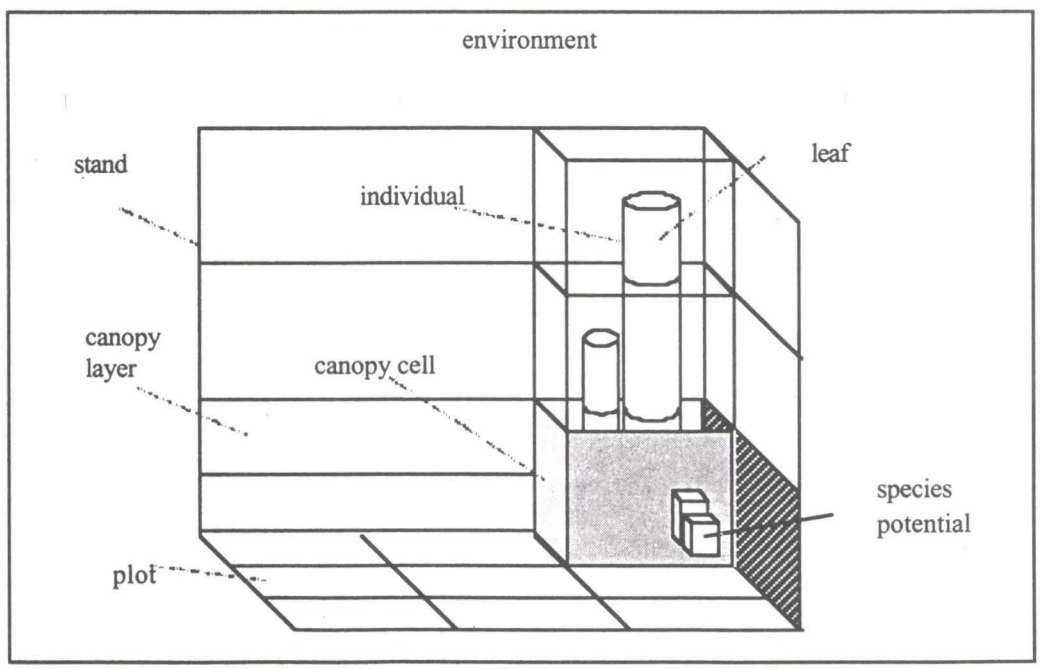

Figure 3.—*Systems of the succession model.*

Table 1.—*Dimensions of model systems*

System	X	Y	Height	Species	Individual
Environment					
Stand					
Plot	x	x			
Species potential	x	x		x	
Individual	x	x			x
Canopy layer			x		
Canopy cell	x	x	x		
Leaf	x	x	x		x

As an example, "Species potential" is defined in 3 dimensions: x, y, and species. The system "Canopy cell" is the intersect of "Plot" and "Canopy layer". It contains methods for the calculation of radiation parameters in the canopy as well as information on the radiation regime *per se*. A "Canopy cell", therefore, is defined in the dimensions x, y and height. A system "Individual" represents an individual tree on a plot. The instances of "Individual" are generated when a tree is established and deleted when a tree dies. The dimensions of such instances are x, y and individual. The intersect of "Individual" and "Canopy cell" creates the system "Leaf" with the four dimensions x, y, height, and individual. This system contains information on the leaf weight and leaf area of an individual tree in a particular canopy cell.

VALUATION

The simulation environment which was introduced in this paper can be classified as a hybrid between an external simulation environment on one hand and a universal programming language without specific simulation tools on the other. A qualitative comparison of our approach with its alternatives is given in tables 2 and 3 below.

Table 2.—*Comparison with universal programming language*

A graphical user interface makes the administration of the succession model more comfortable and simplifies editing work.	+
Methods for the model administration are separated from the succession model and can be universally used for model development.	+
Ecologists can concentrate on the succession model itself and don't have to examine the model administration.	+
The flexible Programming approach causes minor losses in speed and memory.	-

Table 3.—*Comparison with esxternal simulation environment*

Full control of model administration as the source code is available and can be modified if needed.	+
The model, which is to be developed, must not be forced into a prefabricated scheme.	+
Algorithms for the model administration can be optimized. This results in a higher processing speed and a better utilization of storage capacity.	+
The development of the simulation environment is time consuming.	-
No updates and bug-fixes are available.	-

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ON THE FORMULATION OF THE PHYSIOLOGICAL AMPLITUDE OF ALPINE TREE SPECIES IN FOREST SUCCESSION MODELS[1]

Manfred J. Lexer and Karl Hönninger[2]

ABSTRACT.—The combined network of forest inventory, soil and climate data were used to evaluate the environmental response functions from forest succession models. According to the gap-model concept response functions for the effect of temperature and water supply were derived. The new formulations were consistent with phytoecological literature. The comparison of conventional and new response functions showed some expected differences which were mainly due to inconsistencies in the conventionally applied parameterization scheme.

INTRODUCTION

Scenarios of a possible climate change have focused considerable attention on the development of predictive models capable of projecting possible impacts of climate change on forest vegetation. Forest succession models of the "gap" - model concept are considered to be especially useful for this purpose (Shugart *et al.* 1992). In a bottom-up approach these models predict forest vegetation dynamics under varying climatic conditions by integrating growth, reproduction, and death of individual trees on small plots. In contrast to statistical growth and yield models, environmental factors such as temperature, water, nutrients, and light are modeled explicitly. The core of gap-models consists of environmental response functions intended to represent the physiological amplitude ("potential niche") of each species so as to characterize the effect of environmental factors on growth and reproductive processes by modifying species specific growth and reproduction potential. According to Hutchinson (1957), a limited number of key environmental factors is sufficient to characterize the "potential niche" of a species. All gap-succession models consider indices for temperature, water supply, and light. Following the concept of Botkin *et al.* (1972), the environmental response functions are simple unimodal equations.

The shapes of the environmental response functions are based on theoretical ecophysiological considerations and calibrated using map overlays of species distribution and climate parameters. Most researchers have assumed the existence of a close correspondence between the most extreme geographical location in which a species is found and the physiological limits of that particular species (Cramer and Prentice 1988); however, problems with this approach have recently been the subject of debate (Houghton *et al.* 1996, Austin 1992). One problem is that distribution maps for many tree species characterize an ecological ("realized niche") rather than a physiological amplitude ("potential niche"). Thus the effects of interspecific competition, herbivory and post-glacial immigration history are implicitly incorporated in such response functions. Austin (1992) questioned the reliability of this calibration procedure. Another constraint is that the geographical distribution of tree species under actual climatic conditions is the main validation object for a succession simulator and therefore should not be used for model calibration. Pacala *et al.* (1993) suggested the parameterization of forest dynamics models from field measurements and Prentice and Helmisaari (1991) concluded that "a more detailed bioclimatic analysis of species distributions is necessary".

The shape as well as the cardinal points (optimum, minimum, maximum) of the response curves need to be evaluated. Large scale forest inventories record vegetation and site characteristics over a wide geographical range and thus can provide a valuable database for an evaluation study.

OBJECTIVE

In this work we utilized the combined data of the Austrian Forest Inventory, the Austrian Forest Soil Monitoring System, and the climate data from 187 weather stations to evaluate the response functions for the effects of temperature and water supply currently

[1] This work is part of a research project financed by the Federal Ministry of Agriculture and Forestry.

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used in gap-succession models for Central Europe. Our objective was to derive environmental response functions from our database following the rationale of gap-models and compare them with functions currently used in such models.

METHODS AND MATERIAL

Database and Calculation of a Response Variable

Due to the west-east orientation of the Alps, steep vertical and horizontal climate gradients can be found within Austria. Along these gradients we relate an index for the growth vitality to site and stand specific indices for temperature regime and water supply. The database available for analysis consisted of 8,919 sample plots of the Austrian Forest Inventory (AFI), 514 sample plots of the Austrian Forest Soil Monitoring System (AFMS), and 10-year, monthly averages for temperature and precipitation from 187 meteorological stations across Austria spanning the period from 1890 to 1990. AFI data included dominant height by species, stand age, and general site characteristics (Forstliche Bundesversuchsanstalt 1981). Detailed soil attributes included in the AFMS plot data was used to calibrate probabilistic relationships between general site descriptors and physical soil properties (Lexer and Hönninger in review). These empirical relationships were applied to estimate physical soil properties and site water holding capacity for the AFI-sample plots.

Growth vitality index

The actual dominant height at the forest inventory plots was used as an index for a species' growth vitality. The biological rationale for choosing dominant height was the importance of attainable height in the interspecific competition for light and growing space. In addition, this parameter is known to be rather insensitive to silvicultural treatments. A 3-parameter Richards-equation was selected to fit a reference height growth curve as well as an upper and lower enveloping curve for every tree species to the inventory data. To get the growth vitality index (GVI) on a relative scale according to the concept of gap-models we calculated relative height from each individual dominant height and the corresponding value from the reference height curve. The ratio of optimum and reference dominant height is not constant over time. This inherent age trend was excluded by relating each observation to a species specific reference age. In figure 1 the methodology is presented schematically.

Site and Stand Specific Indices for Temperature and Water Supply

To obtain representative temperature and precipitation data for all inventory plots, weather station data had to be interpolated. We first stratified Austria into 53 spatial subunits to provide homogeneous climatic conditions for the following calculations. For every spatial subunit, vertical (for temperature and precipitation) and horizontal (for precipitation) gradients were calculated. With GIS-supported techniques, every inventory plot was related to the nearest weather station. From the climate base data, a representative climate year for each inventory plot was derived. This generated climate year was meant to represent the average growing conditions for the particular stand at the inventory plot. To accomplish this task, species specific weighting factors for the 10-year monthly average values for temperature and precipitation were derived from the reference height increment curves. With this approach, temperature and precipitation data from periods with high increment rates

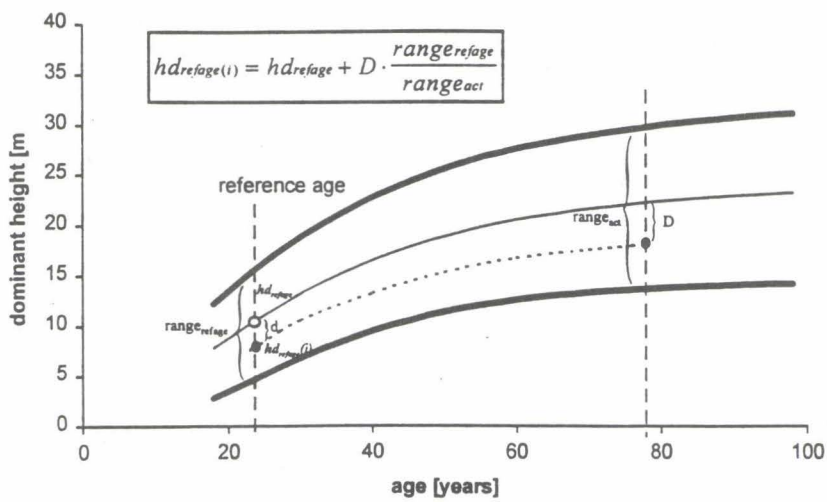

Figure 1.—*Logic for the calculation of the Growth Vitality Index "GVI" from dominant height/age - data.*

were assigned higher weights. Thus, the average life-history of a tree species was incorporated in the derivation of the representative climate year. Finally the weighted temperature and precipitation data was extrapolated to the forest inventory plots by means of the vertical and horizontal gradients, respectively. A topographic modifier accounted for differences in slope and orientation. To integrate soil and climate data, a site water balance was calculated for all forest inventory plots. The potential evapotranspiration (PET) was calculated according to methods given by Thornthwaite and Mather, the actual evapotranspiration (AET) was estimated by modifying PET with reference to the soil water content. From the water balance calculations a soil moisture index for the growing season was calculated (SMI = (PET-AET)/PET). As in all forest succession models for Central Europe (Kienast 1987, Kräuchi 1994, Bugmann 1994), the growing degree days (GDD) above a treshold of 5.5 °C were calculated as an index for the temperature regime.

Establishing Response Functions

In bi-variate scatter plots, the Growth Vitality Index (GVI) for a species was plotted against the pertinent indices for the temperature and water regimes, respectively. These scatter plots usually showed a more or less diffuse cloud. According to the theory of limiting factors, we may expect that environmental factors such as GDD and SMI impose upper ceilings on the response variable GVI without strongly influencing the distribution of the response variable below this ceiling. As the database covered a wide range of possible combinations of environmental factors we concluded that an enveloping curve was characterizing the response of GVI to the site factors GDD and SMI under the assumption that other factors were non-limiting. To circumscribe the bi-variate scatter plots with a mathematical function, we divided the GVI-axis into vertical slices of equal width (Thomson *et al.* 1996). For each slice, we calculated the "ceiling" by averaging the maximum 3 observations of GVI. Subsequently we fitted third or second order polynomials to the "ceiling"-points.

RESULTS

For Scots pine, Norway spruce, European larch, and Common beech, response functions for the environmental indices "GDD" and "SMI" were derived. In all forest gap-succession models, a parabola is used to model the effect of GDD on tree growth. As the shape of third and second order polynomials did not differ substantially for our data we calculated second order polynomials (figs. 2 and 3). Especially for the GDD-response on the "warm" right-hand side, the data base was rather sparse for some species. As an abrupt decrease in GVI at such temperature conditions seemed not to be very realistic, we did not extrapolate the GDD-response curves to get a maximum GDD-value for those species. The response to the soil moisture index "SMI" showed Scots pine to be the most drought tolerant species. European larch responds most rapidly to limited water supply, followed by spruce and beech. From figure 4 it can be seen that none of the species shows optimal GVIs at SMI-values of "0".

DISCUSSION

The ranking of the tree species for GDD-optima and SMI-tolerance according to the derived response functions is consistent with the phytoecological literature (e.g., Ellenberg 1996). With the available data base, maxima and minima for the GDD-response curve could not be defined directly. Reasons were: (i) dominant

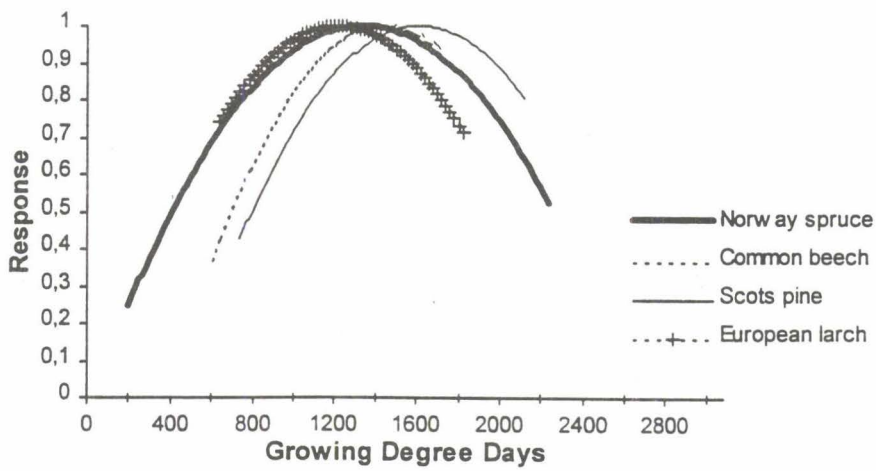

Figure 2.—*GDD-response curves and optima for Norway spruce, Scots pine, European larch, and Common beech as derived from forest inventory data.*

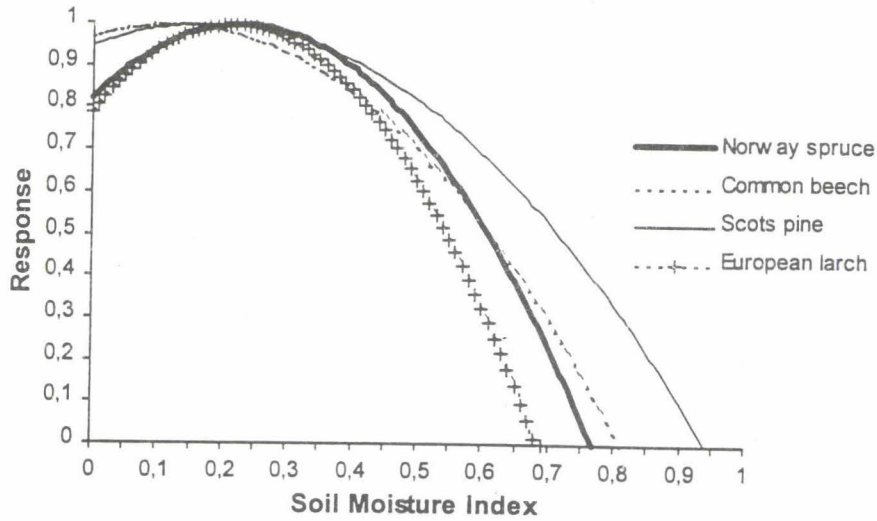

Figure 3.—*SMI-response curves and maxima for Norway spruce, Scots pine, European larch, and Common beech as derived from forest inventory data.*

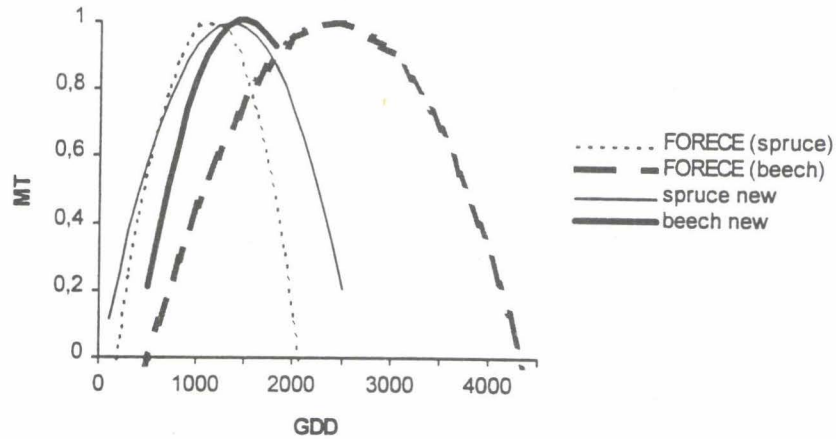

Figure 4.—*Comparison of new response functions for the effect of GDD with corresponding curves in FORECE (Kienast 1987).*

height is a stand parameter (by definition) which is not calculated for uneven-aged stands which dominate at extreme sites (Forstliche Bundesversuchsanstalt 1981), (ii) the Austrian Forest Inventory does not cover the full physiological range of the analyzed tree species. However the derived response functions cover a wide range of possible climatic conditions in Austria. A comparison of the so derived GDD-response functions for beech and spruce, two dominant species in Central Europe, with corresponding curves in FORECE, a prominent forest succession simulator for Central Europe (Kienast 1987), is shown in figure 4.

The "cold" left-hand side of the spruce curve coincides well with FORECE. The extrapolated GDD-minimum for beech was also quite similar between FORECE and the new formulation whereas the optimum GDD-value for beech seems to be clearly lower than in FORECE. On the contrary, spruce is growing fairly well at GDD-values where in FORECE spruce is already excluded. This is due to the fact that the forest inventory data contains data on "secondary" spruce stands outside the "natural" range of that tree species (Ellenberg 1996). A direct comparison of the drought stress response is not possible because of differences in the formulation of the soil moisture index. Instead, for comparison, maximum tolerable drought parameters from four different sources are shown in table 1.

Although both models address essentially the same geographical area (Kienast 1987, Kräuchi 1994), the relative ranking of species differs substantially. For example, Norway spruce can attain substantial dominant heights at periodically dry sites, but is known to be very vulnerable to bark beetle caused mortality. Nevertheless, according to the gap-model concept, environmental

Table 1.—*Comparison of maximum tolerable drought parameters from different authors for European forests*

Species	Source	Maximum Tolerable SMI	Optimum SMI
Norway spruce	Prentice & Helmisaari (1991)[1]	0.12	0.0
	Kienast (1987) [2]	1	0.0
	Kräuchi (1994) [3]	3	0.0
	Lexer & Hönninger [4]	0.72	0.20
Scots pine	Prentice & Helmisaari (1991) [1]	0.24	0.0
	Kienast (1987) [2]	5	0.0
	Kräuchi (1994) [3]	5	0.0
	Lexer & Hönninger [4]	0.92	0.18
Common beech	Prentice & Helmisaari (1991) [1]	0.36	0.0
	Kienast (1987) [2]	2	0.0
	Kräuchi (1994) [3]	3	0.0
	Lexer & Hönninger [4]	0.82	0.13
European larch	Prentice & Helmisaari (1991) [1]	—	—
	Kienast (1987) [2]	2	0.0
	Kräuchi (1994) [3]	3	0.0
	Lexer & Hönninger [4]	0.68	0.19

[a]relative water deficit/year
[b] 5 tolerance classes (each class means 10 percent Dry Days/growing season)
[c]5 tolerance classes
[d]relative water deficit/growing season

response functions are not meant to characterize the susceptibility to bark beetle attacks (Austin 1992). In some cases, the rankings of species are also not consistent with phytoecological and silvicultural literature (e.g., Ellenberg 1996, Burschel and Huss 1987).

CONCLUSION

We have demonstrated that response functions derived from the combined network of forest inventory, soil and climate data may differ substantially from conventionally used formulations. Differences had been expected, given the inconsistencies in the conventionally used parameterization scheme. However, the derived response curves appeared to be consistent with relevant literature. Based on these results, we hypothesize that forest succession models tend to overestimate the extent of forest decline in a changing climate as predicted by various GCM-simulations. The drought stress response appears to be an especially weak representation of the real system. To make environmental response functions in forest succession models more reliable, the analysis of observed responses to environmental factors is needed.

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ANALYSIS OF TIMBER PRICES IN NEW ENGLAND

Donald F. Dennis, Paul E. Sendak, and Thom J. McEvoy[1]

ABSTRACT.—Real stumpage prices for red oak and sugar maple saw logs increased substantially between 1981 and 1996 in New Hampshire and Vermont. Prices for white pine, the most heavily cut species in both States, increased at a moderate but steady rate in New Hampshire, but were relatively stable in Vermont. Large increases in the inventories of low-quality hardwoods contributed to declines in the real prices for hardwood pulp and fuelwood.

INTRODUCTION

In this paper, we update trends in stumpage prices for New Hampshire and Vermont reported by Dennis and Remington (1985), Dennis (1989), and Sendak (1994). Stumpage prices are from the *New Hampshire Forest Market Reports,* published annually by the New Hampshire Cooperative Extension Service, and from quarterly reports prepared by the University of Vermont School of Natural Resources.

Sawtimber prices for New Hampshire are unweighted averages of the midpoints in the reported range in county-level prices for medium-quality saw logs of each species. Hardwood and spruce/fir pulpwood prices are averages for the three northern counties and fuelwood prices are midpoints of the statewide average. The prices are representative of private timber sales, which account for approximately 90 percent of statewide sales.

For Vermont, an average of median prices for county groups was used to estimate State average quarterly stumpage prices. Prices were obtained from a survey of private consulting foresters, loggers, and primary timber processors and include all types of stumpage sales.

TRENDS

Table 1 shows average annual rates of change in real stumpage prices for selected products and species. To remove the influence of inflation, reported nominal prices were converted to real prices using the Producer Price Index (PPI) (all commodity, 1996=100). Ordinary least squares regression was used to estimate annual average change in real prices (Sendak 1991). Figures 1-4 depict these trends

Table 1. —*Average annual rates of change (in percent) in real stumpage prices for six products/species in New Hampshire and Vermont, 1981 to 1996*

Product/Species	New Hampshire	Vermont
Sawtimber		
Sugar maple	3.2	5.8
Red oak	6.0	2.4
White pine	0.9	0.4
Pulpwood		
Hardwood	-0.7	-2.8
Softwood	1.8	0.8
Hardwood fuel	-2.9	-3.2

Real prices for red oak stumpage increased at a remarkable rate during the early 1980's, remained level for several years, and resumed an upward trend in recent years (figs. 1 and 2). Overall, growth rates have clearly outpaced inflation, which averaged 1.7 percent per year from 1981 to 1996 as measured by the PPI. Luppold and Baumgras (1995) reported a 5 percent average annual rate of change in real red oak stumpage prices in Ohio between 1975 and 1993. They attributed this increase to expanding domestic and international demand coupled with relatively limited stumpage supplies.

Although prices for red oak increased in both States, there were differences. Average 1996 prices were $272 per thousand board feet (mbf) International 1/4-inch rule in New Hampshire (fig. 1) versus $292 in Vermont (fig. 2). In New Hampshire, about 26 million board feet (mmbf) of red oak are harvested each year versus about 8 mmbf in Vermont.

[1] **Donald F. Dennis** and **Paul E. Sendak**, Northeastern Forest Experiment Station, P.O. Box 968, Burlington, VT 05402 and P.O. Box 640, Durham, NH 03824, respectively. **Thom J. McEvoy**, University of Vermont, School of Natural Resources, Burlington, VT 05405. Summary of poster presentation at SSAFR.

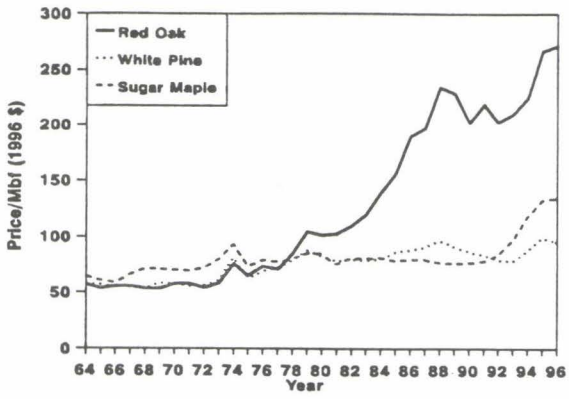

Figure 1.—*Real prices for medium-quality red oak, white pine, and sugar maple sawtimber in New Hampshire.*

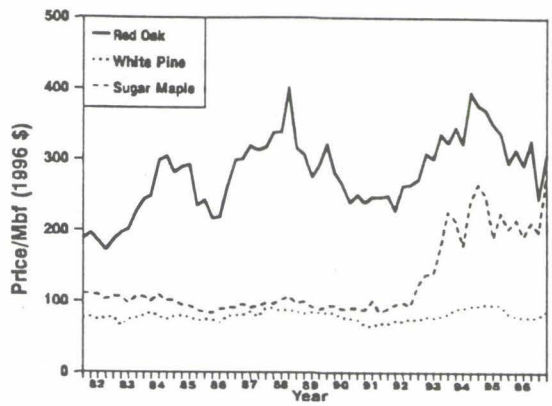

Figure 2.—*Real prices for red oak, white pine, and sugar maple sawtimber in Vermont.*

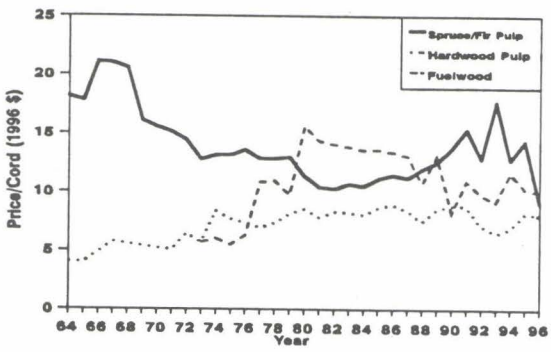

Figure 3.—*Real prices for hardwood and spruce/fir pulpwood and softwood in New Hampshire.*

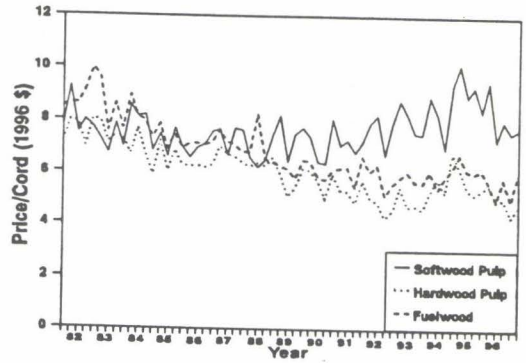

Figure 4.—*Real prices for hardwood and softwood pulpwood and fuelwood in Vermont.*

Long-stagnant sugar maple prices have recovered. The average 1996 price for medium-quality sugar maple was $135/mbf in New Hampshire versus $219/mbf in Vermont (figs. 1 and 2). This difference may be partially due to differences in reporting between the States. The New Hampshire price is for medium-quality saw logs, while one range for all quality grades is reported in Vermont. Sugar maple is the most heavily cut hardwood in Vermont consisting of 31 mmbf, or 18 percent of the State's annual saw log harvest. In New Hampshire, only 9 mmbf of sugar maple are cut (4 percent of the annual saw log harvest).

White pine, the most heavily cut species in both States, accounts for 50 percent of the annual saw log harvest in New Hampshire and 20 percent in Vermont. Prices for white pine have increased at a moderate but steady rate in New Hampshire (fig. 1), but were relatively stable in Vermont (fig. 2). In 1996, prices were slightly higher in New Hampshire at $95/mbf (fig. 1) than in Vermont, where the price was $93/mbf (fig. 2).

The annual pulpwood harvest in both States approximately equals the saw log harvest in volume. Stumpage prices for low-quality hardwoods (including fuelwood) have declined (figs. 3 and 4). Large increases in inventories of low-quality hardwoods have contributed to declines in the real prices for hardwood pulp and fuelwood. Of course, reductions in cost of alternate fuels also played a role in declining fuelwood prices.

Mortality in spruce/fir stands caused by spruce budworm and subsequent reductions in supply partially account for the slight upward trend in prices for softwood pulp. In New Hampshire, where only spruce/fir pulpwood was included, prices have increased at an average rate of 1.8 percent per year. In Vermont, where all softwood species are included, prices increased at an average rate of 0.8 percent (table 1)

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INTEGER SOLUTIONS FOR MODEL I HARVEST SCHEDULING LP PROBLEMS: TESTING THE R-RATIO HEURISTIC

Luiz C.E. Rodriguez and John P. McTague[1]

ABSTRACT.—Rodriguez (1994) suggested a search procedure that selects a single forest management prescription for each forest management unit, given production constraints. The procedure was named the *R-ratio heuristic* and it was based on the principle that production constraints could be disregarded at the beginning of the solution process. Area and production constraints are two important sets of constraints in a Model I (Johnson and Scheurman 1977) harvest scheduling linear programming problem. Disregarding production constraints at the beginning makes the solution very simple and the selection of the best prescription for each management unit is the obvious answer. Therefore, the problem becomes a matter of replacing an initially selected prescription with a new one more capable of achieving production feasibility. The *R-ratio* guides the replacement of prescriptions, one at a time, if used as the selection criterion. The idea is to replace an initially selected prescription with the one presenting the highest *R-ratio.* The *R-ratio* divides *contribution to feasibility (f)* by *reduction in the objective function (o)*. The ongoing tests involve different methods for calculating *f* and *o*, and alternative strategies to deal with the set of initially selected, but later on rejected prescriptions. Preliminary work shows promising results when comparing the R-ratio heuristic method with traditional branch-an-bound integer programming algorithms.

INTRODUCTION

Spatial limitations and the regulation of forest operations are two of the most important constraints in a harvest scheduling problem. Mathematical programming has been used as the most suitable technique to model such problems. Among the most popular formulations, the type I linear programming harvest scheduling model (Johnson and Scheurman 1977) defines decision variables as the acreage in each management unit assigned to forest management prescriptions fully prescribed for the whole planning horizon.

In model I, production and spatial constraints are tightly linked as shown in formulation (1).

$$(1)\quad \begin{cases} Max\ Z = \sum_i \sum_j c_{ij} x_{ij} & \text{with } x_{ij} \geq 0 \\ \text{subject to:} & \\ \quad \text{Available acreage:} & \sum_j x_{ij} \leq A_i \qquad (i = 1,\ldots,I) \\ \quad \text{Minimum production:} & \sum_i \sum_j v_{ijt} x_{ij} \geq V\min_t \qquad (t = 1,\ldots,T) \end{cases}$$

where

- Z = total discounted revenue from harvesting plan
- c_{ij} = discounted net revenue from management unit i if management prescription j is used
- x_{ij} = management unit i acreage assigned to management prescription j
- A_i = management unit i total acreage
- v_{ijt} = per-acre output in management unit i harvested in period t if prescription j is used
- $Vmin_t$ = minimum harvest production requirement in period t
- I = total number of management units
- T = total number of periods in planning horizon

The integer version of the same problem allows for the more realistic assumption that only one prescription may be assigned to a management unit. The alternative would be to make x_{ij} a binary *0-1* decision variable, and formulation (1) becomes formulation (2).

$$(2)\quad \begin{cases} Max\ Z = \sum_i A_i \sum_j c_{ij} x_{ij} & \text{with } x_{ij} = 0,\ 1 \\ \text{subject to:} & \\ \quad \text{Available acreage:} & \sum_j x_{ij} \leq 1 \qquad (i = 1,\ldots,I) \\ \quad \text{Minimum production:} & \sum_i A_i \sum_j v_{ijt} x_{ij} \geq V\min_t \qquad (t = 1,\ldots,T) \end{cases}$$

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Formulation (2) comes handy when dealing with forest planning problems that include adjacency constraints. For such formulations Meneghin *et al.* (1988) suggested treating adjacency with *'combining'* constraints to represent the mutually exclusive conditions for a group of management units, instead of the more intuitive pairwise formulation. More recently Murray and Church (1996) argue that the work of Meneghin *et al.* (1988) can be framed as a special topic in a broader class of problems studied by the network/graph theory called *'cliques'*.

A set of mutually adjacent units constitutes a clique, and framing a problem this way adds more resolution to the set of available area constraints. The more realistic assumption of indivisible prescription assignment to management units and the greater spatial resolution imposed by adjacency constraints make formulations like (2) a necessity. Unfortunately, formulations where variables take on strictly integer values are problems in combinatorics, and are much more difficult to solve than problems with continuous variables.

Complexity arises from computational difficulties imposed by the curse of dimensionality, i.e., algorithms used to solve formulation (2) present worst-case scenarios where performance is bounded by an exponential function of the problem size. Problems with even a few hundred variables can easily surpass the limits of such algorithms.

In this paper we present some initial results obtained with a new heuristic called the *R-ratio* heuristic (Rodriguez 1994). The R-ratio heuristic follows the principles of other heuristics, and it was developed based on intuition and some insights offered by the more mathematically rigorous *Simplex* algorithm. It cannot guarantee an exact optimal solution, but is a *'good'* heuristic given that it offers *'good'* solutions (often near optimal) for very large integer problems in very few iterations.

THE R-RATIO HEURISTIC

One interesting fact about formulation (2) is the role of the production constraints in tightening the problem. These are the *'hard'* constraints in the sense that, if they were dropped, a trivial solution would immediately exist. The optimal solution for this unconstrained problem chooses the prescription associated with the highest objective function coefficient for each management unit. Obviously the unconstrained solution will most of the time be infeasible with respect to formulation (2), although it is unequivocally associated with the highest value possible for the objective function.

The R-ratio heuristic is based on the following rationality: starting with the unconstrained solution, it is possible to replace selected management prescriptions with non-selected prescriptions in such a manner that eventual deficits (unattained minimum volume constraints) can be reduced at a minimum decline in the objective function value. Some *'inspired'* ideas are derived from the simplex algorithm:

- There must exist an initial solution, after relaxation of some constraints, that selects the best prescription in each management unit (the unconstrained solution), and that therefore generates the highest objective value possible.

- From the set of non-selected prescriptions, select one to enter the *'basis'* that results in the best possible contribution to deficits per unit of reduction in the objective function, i.e., the *R-ratio* (this step is similar to the process of selecting the new variable to enter the basis in the simplex algorithm).

- The variable to be replaced (variable *'leaving the basis'*) is easily located because there can be only one prescription per management unit (to ensure integer solutions), and it is easy to identify what management unit is associated with the newly selected variable (variable *'entering the basis'*);

- Repeat the process until all production deficits are eliminated.

Figure 1 outlines the sequence of steps needed to implement the R-ratio heuristic. There are basically four main routines in the heuristic:

***Data formatting*:** This routine checks for the existence of basic information: management unit names, forest prescriptions for each management unit, detailing when and how much production is expected from each prescription along the planning horizon, forest prescription discounted revenues, management unit areas, and expected output goals per period in the planning horizon. One special feature of the R-ratio heuristic is the use of parameters for adjusting the search strategy. The R-ratio heuristic stores the discarded (replaced) x_{ij} variables in a special set for a potential return later into the basis. The user-defined parameter α of the heuristic indicates the iteration number when the discarded set must be searched for a variable to return to the basis. Once this iteration is reached, the set of discarded variables is re-visited every β iterations. The value of β defines the second

- **Input data:**
  - *Prescriptions* table:
    - Units, Forest prescriptions, Values
  - *Land* table:
    - Units, Acreage
  - *Targets* table:
    - Period, Production targets
- **Create sets:**
  - S - Best prescriptions, one for each forest unit, based on their objective function value.
  - N - Non-selected prescriptions, i.e., all prescriptions not in set S.
  - D - discarded prescriptions, empty at beginning.
- **Input heuristic parameters:**
  - α - number of iterations until prescriptions start to be selected from set D.
  - β - iteration interval in between two prescription selections from set D.
- **While production deficits and non-selected prescriptions exist, do phase I:**
  - *if selecting from set N, do routine to reduce deficits at minimum reduction (cost) in objective function:*
    - Select prescription in set N based on best contribution to deficit reduction at minimum cost.
    - Transfer selected prescription from N to S.
    - Transfer discarded prescription from S to D.
  - else, do
  - *routine to retry previously discarded prescriptions (selecting from set D)*
    - Choose best prescription in D based on largest contribution to deficit.
    - Transfer selected prescription from D to S.
    - Transfer discarded prescription from S to D.
  - Calculate production deficits.
- **If a feasible schedule was found, do phase II:**
  - *routine to improve objective function value*
    - Choose the best prescription in sets D or N that does not cause production deficit and improves the objective function value.
    - Transfer selected prescription from D or N to S.
    - Transfer discarded prescription from S to D.
  - Update production flow.
  - Break if the objective function value cannot be improved.
- **Report results.**

Figure 1.—*R-ratio heuristic simplified flow-chart.*

parameter of the heuristic process. Different combinations of parameters α and β establishes different search strategies for better solutions by avoiding a single path to a local solution.

Phase I (searching for feasibility): The *R-ratio* is computed in each iteration to rank the non-selected variables. The x_{ij} variable of formulation (2) associated with the highest R-ratio is then selected to enter the basis. The newly selected variable prescribes a different management prescription *j* to management unit *i* with respect to the current variable in management unit *i* that it replaces, and convergence to feasibility (if it exists) can be easily obtained in a steady pace after a certain number of iterations. The number of iterations is dependent on how infeasible the problem was with the initial solution and the presence of *good* alternative prescriptions in the problem. Alternatively, every time the heuristic *'visits'* the discarded set of variables, the ranking process selects the best variable, not by reliance on the *R-ratio* as a guide, but rather on their total contribution to deficit reduction. The assumption here is that these variables were already selected before, and they do not need to be tested again as good candidates for increasing the objective function value.

Phase II (trials to improve the objective function value): Once feasibility is reached, each new iteration in the *R-ratio* heuristic method ranks jointly the two sets of discarded and non-selected variables by a new criteria. This time the ranking process is sorted by increases to the objective function value. Only x_{ij} variables that maintain the solution feasible are considered. The process is terminated when it is impossible to further increase the objective function value with x_{ij} variables that maintain a feasible solution.

Report writing: storage of last iteration results and performance parameters.

HEURISTIC IMPLEMENTATION

The heuristic is heavily based on sorting routines. A prototype program called FOREX was designed to generate a testing environment. More programming effort was put on having control over events than on speed. Therefore, processing time can certainly be reduced in future versions of the program. The present environment was designed for implementation of several refinements in the heuristic that resulted in fewer iterations for reaching feasibility. Better performance in time is expected in the near future by refining the code for speed.

THE TESTING PROBLEMS

Initial tests with the R-ratio heuristic were based on the performance observed when searching for integer solutions of small and medium sized harvest scheduling type I basic formulations. Although solutions for larger problems can be obtained by the R-ratio heuristic in reasonable amounts of time, only small and medium sized problems are reported here because optimal integer solutions, obtained with the branch and bound algorithm, were also computed for these problems. The four problems listed in table 1 serve as testing problems.

Forest prescriptions included as alternative management regimes differ primarily in terms of the timing of timber harvests (table 2). In all four cases, the valuation criterion was simply set as the total volume a given prescription would produce over the planning horizon.

Table 1.—*Sizes of the testing problems*

Problem number	Management units	Average number of prescriptions	Planning horizon	Total number of 0-1 integer variables
			periods	
1	20	5	21	100
2	30	5.2	21	150
3	70	8.7	15	650
4	152	17	15	2,584

Table 2.—*Harvest timing of forest prescriptions considered for each problem*

Problems	Forest type	(Prescription number) Comma delimited harvest timing
1 and 2	1	(1) 3, 8, 13, 18 (2) 4, 10, 15, 21 (3) 5, 10, 16, 21 (4) 6, 12, 18
	2	(1) 1, 7, 13, 19 (2) 1, 8, 14, 21 (3) 2, 8, 15, 21 (4) 2, 9, 16
	3	(1) 4, 9, 14, 19 (2) 4, 10, 15, 21 (3) 5, 10, 16, 21 (4) 5, 11, 17
		(1) 1, 6, 11, 16, 21 (2) 2, 7, 13, 18 (3) 3, 8, 15, 20 (4) 1, 7, 12, 18;
	4	(5) 2, 8, 14, 20 (6) 3, 9, 16 (7) 1, 8, 13, 20 (8) 2, 9, 15
		(9) 3, 10, 17
3		(1) 1, 12 (2) 2, 9, 15 (3) 2, 12 (4) 1, 8, 14 (5) 3, 10 (6) 3, 13
	1	(7) 4, 11 (8) 4, 14 (9) 5, 11 (10) 5, 14 (11) 6, 12 (12) 6, 15
		(13) 7, 13 (14) 7 (15) 8, 14 (16) 8 (17) 1, 9, 15
4	1	(1) 1, 8, 15 (2) 2, 9 (3) 3, 10 (4) 4, 11 (5) 5, 12 (6) 6, 13 (7) 7, 14
	2	(1) 1, 11 (2) 2, 12 (3) 3, 13 (4) 4, 14 (5) 5, 15 (6) 6 (7) 7 (8) 8
		(9) 9 (10) 10
	3	(1) 1,14 (2) 2, 15 (3) 3 (4) 4 (5) 5 (6) 6 (7) 7 (8) 8 (9) 9 (10) 10
		(11) 11 (12) 12 (13) 13
	4	(1) 1, 9 (2) 2, 10 (3) 3, 11 (4) 4, 12 (5) 5, 13 (6) 6,14 (7) 7,15 (8) 8
	5	(1) 1, 7, 13 (2) 2, 8, 14 (3) 3, 9, 15 (4) 4, 10 (5) 5, 11 (6) 6, 12
	6	(1) 1,10 (2) 2,11 (3) 3,12 (4) 4,13 (5) 5,14 (6) 6,15 (7) 7 (8) 8 (9) 9
	7	(1) 1,12 (2) 2,13 (3) 3,14 (4) 4,15 (5) 5 (6) 6 (7) 7 (8) 8 (9) 9 (10) 10
		(11) 11

It is important to note that the existence of several harvest interventions in one single prescription augments the difficulty of finding an integer solution. Problems 1 and 2 incorporate such characteristics to compensate for their relatively small sizes. Problems 3 and 4 offer a larger number of prescription alternatives per management unit, and consequently more flexibility in generating feasible solutions.

Problem 1 considers a 21 year planning horizon and minimum production constraints of 5,000.00 units of volume per year. Problem 2 presents the same time span and an annual demand of 8,000.00 units of volume per year. The periodic minimum amount imposed in problem 3 was 4,000,000.00 every 6 years, making for a planning horizon of 90 years. In problem 4 the first five periods are 2-year periods and the other 10 periods are 4-year periods, with an annual fixed demand of 2,500,000.00 units of volume. Tests were made on computers based on 100 *Mhz Pentium* processors.

RESULTS

Objective function values obtained varied by problem and search strategy (i.e., combination of the α and β parameters) as shown in tables 3 - 7. Many combinations resulted in feasible solutions. Empty cells represent cases for which the heuristic search strategy could not find any feasible solution before running out of non-selected x_{ij} variables to enter the *basis*. Results are reported as objective function percentage values of the best known integer solution found with the branch and bound algorithm.

For problem 1 (table 3), many different search strategies resulted in objective function values that are at 99 percent of the optimum. Frequently re-selecting discarded variables to re-enter the *basis* (i.e., choosing small values for β) proved to be the most efficient strategy. Results reported in table 3 took an average of 58.1 iterations, obtained at a rate of 0.35 seconds per iteration.

For problem 2, and based on the experience obtained with problem 1, small values of β were tested against a larger number of α values. This is a slightly larger version of problem 1, and results presented in tables 4 and 5 still show good performance for small values of β, even at larger values of α. Results in tables 3 and 4 were computed after an average of 103.3 iterations at a rate of 0.5 seconds per iteration.

An optimal integer solution for problem 3 was not found with the resources available at the time it was analyzed. The problem has to be analyzed by more advanced solvers that soon will become available to the authors. To make comparisons possible though, heuristic results in table 6 use the optimal solution for the regular linear programming (non-integer) formulation as a reference. This optimal non-integer solution assigns one single prescription to 62 management units and splits the other 8 into two or more prescriptions each. The R-ratio heuristic not only solved very efficiently the problem, but it also offered several *'good'* solutions, taking an average of 122.5 iterations at a rate of 0.8 seconds per iteration.

The largest problem, with 2,584 binary integer variables and a 15-period planning horizon, was obviously more demanding in time. Each iteration took an average of 4.1 seconds, which compared to the processing times of problems 1, 2, and 3 still indicates a possible linear relationship between processing time and problem size, instead of a bounding exponential limit. The best integer solution objective function value used as a reference proved to be 2.35 percent better than the best heuristic strategy (α=80 and β=25). Average number of iterations in this case was 585.3 per run.

Table 3.—*Objective function values (expressed as a percentage of the best objective function obtained via integer solution) obtained with the R-ratio heuristic for problem 1*

$\beta\backslash\alpha$	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2	-	-	-	-	-	98.9	98.9	99.4	99.0	99.0	99.0	-	-	99.3
3	99.6	99.5	99.6	99.5	99.6	99.5	99.5	99.2	98.7	-	98.7	-	95.5	95.5
4	96.8	-	95.4	96.8	-	95.4	96.8	-	-	-	-	-	99.1	99.2
5	98.0	97.7	98.2	97.9	98.0	97.7	98.2	97.9	-	98.1	98.5	97.9	-	98.1
6	97.8	-	95.3	98.0	97.9	97.8	-	95.3	98.0	-	-	97.0	95.3	98.0
7	-	97.8	97.8	99.0	98.4	97.7	-	97.8	97.8	99.0	94.5	99.4	-	97.8
8	97.7	98.0	-	-	97.9	97.7	-	97.7	98.0	-	-	-	97.9	97.6
9	97.7	98.5	-	97.8	97.8	-	95.3	-	97.7	98.5	-	97.8	-	97.1
10	-	97.1	97.9	-	97.8	98.1	96.4	97.8	97.8	-	97.1	97.9	-	98.1

Table 4.—*Objective function values (expressed as a percentage of the best objective function obtained via integer solution) obtained with the R-ratio heuristic for problem 2*

β\α	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2	-	99.0	99.0	99.0	99.0	-	-	-	98.9	98.9	98.9	99.0	98.3	99.1
3	-	99.2	-	99.2	-	99.2	98.8	99.2	98.6	98.3	98.7	-	98.4	99.4
4	98.1	99.2	98.7	99.2	99.2	98.7	99.2	99.2	98.7	-	-	99.0	98.4	98.3
5	99.3	-	98.3	98.0	99.3	-	98.3	98.0	99.3	-	-	-	98.6	-
6	-	-	-	97.9	-	-	-	-	97.9	-	-	98.2	98.6	-
7	-	-	-	-	-	-	99.4	-	-	-	-	-	97.8	-

Table 5.—*Objective function values (expressed as a percentage of the best objective function obtained via integer solution) obtained with the R-ratio heuristic for problem 2—continued from Table 4*

β\α	16	17	18	19	20	25	30	35	40
2	-	98.0	98.8	-	98.7	-	98.9	-	99.3
3	99.3	99.1	99.1	98.1	98.7	98.8	98.9	-	98.8
4	98.8	-	98.0	-	-	98.7	98.8	99.1	-
5	98.6	-	98.0	-	-	-	99.0	98.5	98.6
6	98.6	-	98.0	-	-	-	99.0	98.5	98.9
7	98.6	-	98.0	-	-	-	99.0	98.5	98.9

Table 6.—*Objective function values (expressed as a percentage of the best objective function obtained via non-integer linear programming solution) obtained with the R-ratio heuristic for problem 3*

β\α	20	25	30	35	40	45	50	55	60
5	98.0	98.2	98.4	98.3	98.5	97.5	98.4	98.6	97.5
10	98.5	97.4	97.9	98.3	98.4	98.1	98.1	98.3	97.6
15	97.5	98.0	97.8	97.1	98.8	98.3	98.3	97.0	97.8
20	98.0	97.9	98.1	97.2	98.6	97.9	97.4	97.4	98.3
25	98.6	98.2	97.6	97.4	98.6	98.2	97.3	98.0	98.2
30	98.2	98.3	96.8	98.3	98.2	97.9	97.1	98.3	98.4
35	97.5	97.8	97.5	97.5	98.2	97.6	97.8	97.2	98.1

Table 7.—*Objective function values obtained with the R-ratio heuristic for problem 4 (percent of best integer solution objective function value)*

β\α	50	60	70	80	90	100
20	97.1	96.8	97.0	96.7	96.9	96.8
25	97.6	97.7	97.6	97.7	97.0	97.0
30	97.4	97.4	95.8	97.0	96.7	96.5
35	97.3	97.3	96.8	97.4	96.9	97.6

CONCLUSION

The R-ratio heuristic was developed with one objective in mind: to develop a simple process that can result in *'good'* integer solutions for Model I harvest scheduling linear programming problems. On going tests with the R-ratio heuristic have shown promising results. Definitive conclusions will be obtained after some further changes in the heuristic.

Among the changes, still to be implemented, are two that are aimed at speeding up the search routines: one by reducing the number of updates in the vector of R-ratios for the set of non-selected x_{ij} variables, and another that introduces strong changes in the converging feasibility path, by replacing more than one variable at a time. It is plausible that strong changes during phase I will shift the feasibility convergence path. Strong changes at the beginning would set the course towards very different paths with combinations that may generate heuristic solutions that are even closer to optimal integer solutions.

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ELECTRONIC MARKETING FOR MICHIGAN'S FOREST-BASED INDUSTRIES

Demetrios Gatziolis, James Stevens, and Matthew Thorburn[1]

THE DIRECTORY

The Michigan Department of Natural Resources Forest Management Division (MDNR) has maintained a directory of Michigan primary and secondary wood products producers and manufacturers for the past 12 years. The records were kept on a mainframe computer and the information was disseminated by periodic paper bound publications. The company list is updated regularly and currently has about 2,200 participating wood products firms. In 1995 the data base was moved from the mainframe to a PC. An earlier project transformed the flat file data base to a relational format.

THE PROJECT

This project was initiated to produce three primary products: (1) a normalized data base for the PC environment that allows for form-based data entry/editing, (2) a copy of the data base to be circulated in searchable form using CD ROM format, and (3) a searchable World Wide Web version of the data base. It is one of very few examples in the country of a searchable, online, or distributable directory of forest products businesses and their products. It allows a unique opportunity for buyers from around the world to match their needs with the products of Michigan and join buyers and sellers in a cost-effective way.

THE TOOLS

The tools used in the creation of the data base were Microsoft Access 7.0 for Windows 95, Microsoft Access Developer's Toolkit for the PC/CD version, and Cold Fusion (fig. 1) for the searchable Web version operating under a Windows NT environment. The revised data base is driven by an automated front-end developed in Microsoft Access of push button selections and drop-down menus, allowing even a beginning user the opportunity to access data and develop reports. Referential integrity and error checking validation is built into the data base structure. The automated forms are used by the DNR staff to keep the records up-to-date.

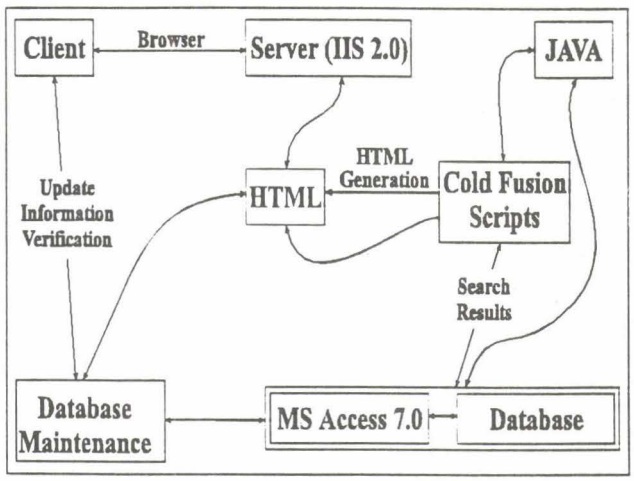

Figure 1.—*Information flowchart for Web Server data base.*

The Web and CD ROM versions are meant to be distributed to wider audiences than the current paper copies. Their interfaces are searchable by company characteristics, e.g., species and materials used in production, products manufactured, equipment and services available, in-state location, firm size, interest in exporting, etc. The web product will be continually updated while the CD product, a transportable, easily-distributable format, can be periodically released with updated information. The web interface includes a response section whereby users can directly e-mail the MDNR with questions about or corrections to the data base. Direct hyperlinks can be established for companies that have electronic mail or home pages of their own for immediate connections from interested parties. The underlying data base resident on the MDNR network still allows production of the traditional paper bound report as well as additional opportunities for analysis of the data.

PROJECT OBJECTIVES

The short-term objectives of this project were to:

- provide online users of the World Wide Web up-to-date information about Michigan forest products businesses, their specific products and services, and a means of contacting them;

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- provide a similar search tool via CD ROM (or other mass storage medium) for distribution to those who do not have access to the World Wide Web; and

- provide the MDNR with an efficient means of updating and maintaining this data base.

The long-term goals are to:

- increase the opportunities for Michigan forest products businesses to market their products nationally and internationally,

- provide increased economic development opportunities for value-added processing in Michigan through quick access to continually updated information, and

- provide an ongoing data base for rural development efforts in Michigan.

The project:

- improves access to sophisticated resources for small forest-based businesses by connecting them to potential customers using technology that may be beyond their individual resources,

- improves the competitiveness of existing industries,

- provides timely information,

- highlights forest resource based economic opportunities,

- increases the awareness of the importance of the State's forest-based economy,

- creates a high profile tool for potential clients world wide to become aware of Michigan's forest products, and

- shrinks the search and response time of potential buyers to allow them direct access to information about Michigan forest products.

This project teamed the Michigan Department of Natural Resources, Michigan State University Department of Forestry, and the forest products businesses of Michigan in a working partnership. It was initiated through the industry- and land owner-based Sustainable Forest Development Roundtable.

DATA BASE

The project information is included in a Microsoft Access 7.0 normalized data base, an improvement over the pre-existing mainframe data base. The data base currently contains 32 tables, linked together with unique identifiers, the company ID being the one most frequently employed (fig. 2). Advantages of the normalized data base include: (a) simpler data base update and maintenance; (b) companies sharing the same name, or having more than one facility at different locations can be included without confusion; (c) eliminates redundant data and/or empty data base cells; (d) easy incorporation or modification of look-up (i.e., explanatory) code tables; (e) flexible table-record size; (f) data base integrity not affected by record, or even table, removal/addition; (g) built-in enforcement of referential integrity; (h) minimized query (data base search) time; (i) smaller PC random access memory (RAM) requirements; and (j) faster development of data indices.

CD ROM

The CD ROM product contains the data base along with the MS Access environment and modules. Installation is easy, suited to the inexperienced user, and based on a self-inflating executable file, also provided with the CD ROM. The working environment is user-friendly, with push-buttons and drop-down-menus. The user has the option of searching for one or many characteristics. The results of the user-specified query elements are presented either as screen reports, saved as spreadsheet files, or may be printed as tabular reports. The fact that the information is available locally (on the clients PC) provides for high speed, network independent, data base search results. Regular updates of the CD are planned. Production of the updated CD is much more cost effective than the traditional paper copy although this medium will be continued for users without computer access.

The CD product was developed for use with PC's running Windows 95. Due to the variety of systems and monitors in use, the screens were created to fit the lowest common denominator resolution (640X480 pixels). Help screens walk the user through the set up process and through the selection of search options in the data base itself. The forms used in the creation of the interface were developed using Visual Basic for Applications provided with Access with additional controls provided in the Access Developer's Toolkit. The user navigates through a minimal series of screens to find selections. Tabbed selections within a screen to minimize the paging back and forth through screen selections. Pop-up windows with selections provide the user with choices and the resulting companies that meet the criteria of these choices. Output to screen, files or print is activated by button controls.

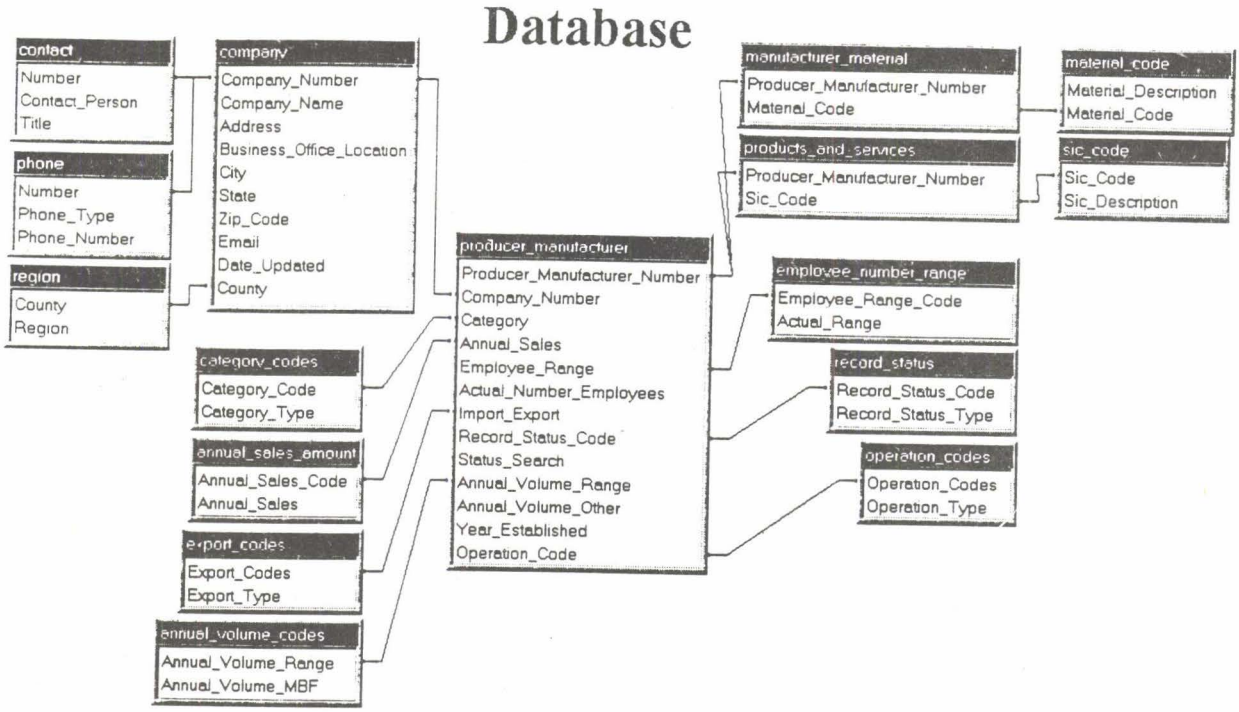

Figure 2.—*Data base structure.*

WEB TOOL

In the Web application, information is transferred from the server, where the data base resides, to the clients' computers and therefore is network speed dependent, but, on the other hand, information can be continuously updated. The application is based upon Cold Fusion 1.5 software package (CF) and additional CGI and JAVA scripts aiming at improving its functionality and visual aesthetics. CF can be viewed as a collection of CGI-type scripts (fig. 3) that provide communication between query forms, filled-in by the client, and the data base. The application utilizes frames for better client-data base interaction with the underlying HTML code (fig. 4) developed manually. Its appearance has been tested for consistency against different screen resolutions (640 x 480 - 1280 x 1024 pixels) and the majority of the Web browsers including, MS Internet Explorer 3.0, Netscape Navigator 2.0, 3.0, and 3.0.1, NSCA Mosaic, Spry, and SpyGlass.

Due to the network speed dependency, it is imperative the data transferred per client request not to exceed a prespecified byte threshold. Complying with this requirement the application partitions the query output in increments of 25 records. The CGI scripts, apart from controlling the data base search and formulating the retrieved output, enhance the data base security, prohibiting direct interaction between the data base and the clients, verify the accuracy of the client-submitted requests providing directions when an incompatible request is encountered, monitor the clients' IP address and browser type used, provide submission of comments, e-mail messages, and data base update information.

JAVA scripts are used for presenting summary data base statistics in graphical format. Clients using browsers that do not support JAVA scripts are prompted to web addresses where contemporary browsers are available as free downloads. A "How to" link can be seen in any of the application's pages.

The queries currently available in the application include Company Location, Products/Services offered, Materials/ Species used, as well as a combination of these query categories (fig. 5). The Products/Services, Materials/ Species information within the data base have a hierarchical structure. The client is prompted to navigate through the hierarchy, find the entry of interest, and get the code needed for the search to be launched. This approach has the advantage that the client can search the data base for a particular piece of information without having to be familiar with the wood industry related vocabulary. Formatted search output can be converted to a hard copy provided that the client has a printer available locally.

Companies listed in the data base can send updated information directly to the person responsible for the data base maintenance by simply filling out the online form provided. Any existing information is already available in the form so that the company representative need change only the parts to be modified. An empty form is also available for companies not currently included in the data base. The updated information is delivered to the MDNR only if contact information with the company in question is submitted as well (for verification purposes). Update requests that repeatedly fail to provide contact information can be prohibited from having access to the application via the IP address tracking if desired.

TESTING

The CD ROM product as well as the web application have been exposed to a broad group of reviewers including faculty members at Michigan State University, MIDNR employees, wood industry representatives, and several anonymous individuals. Their comments have been carefully considered and in many cases incorporated in the applications. Recently, students in the Department of Forestry were asked to use and provide their comments on the web application. They concluded that the use of the application was intuitive and use of the data base considerably enriched their knowledge regarding the wood industry of the State of Michigan.

The web site can be reached at http://forestry.msu.edu/mwii/invent.htm and the CD ROM will soon be available for purchase through the MDNR Forest Management Division.

```
<DBQUERY Name = "FindTotalNumberOfRecords"
        DataSource = "FOREST PRODUCTS"
                SQL = "SELECT Company_Number, Company_Name FROM Company
                WHERE Company_Number IN (SELECT Company_Number
                                FROM Producer_Manufacturer
        WHERE Status_Search = 1) AND Company_Name LIKE Form.Company_Name#%'">
        <DBIF #Form.EmpNum# IS NOT "">
        <DBIF #Form.EmpNum# LESS THAN "5" >
        <DBSQL SQL = " AND Company_Number IN (SELECT Company_Number
        FROM Producer_Manufacturer
        WHERE Actual_Number_Employees < 50) ">
        </DBIF>.....
                                .........
```

Figure 3.—*Cold fusion Code example, Query Processing, and Linking to Data base.*

```
<html>
<body link = #0000ff vlink = #187090 bgcolor = #ffffff><br>
<table border = 1 width = 100%>
        <tr>
        <td>
        <table width = 100%>
        <tr align = middle>
        <td>    <a href = "/scripts/dbml.exe?template = /mwii/q1.dbm">
        <b> General Search </b></a><br>
        <a href = "/scripts/dbml.exe?template = /mwii/q2.dbm">
        <b> Search by Location </b></a><br>
                        .........
```

Figure 4.—*Hyper Text Markup Language (HTML) Code example, Query Development, and Screen Configuration.*

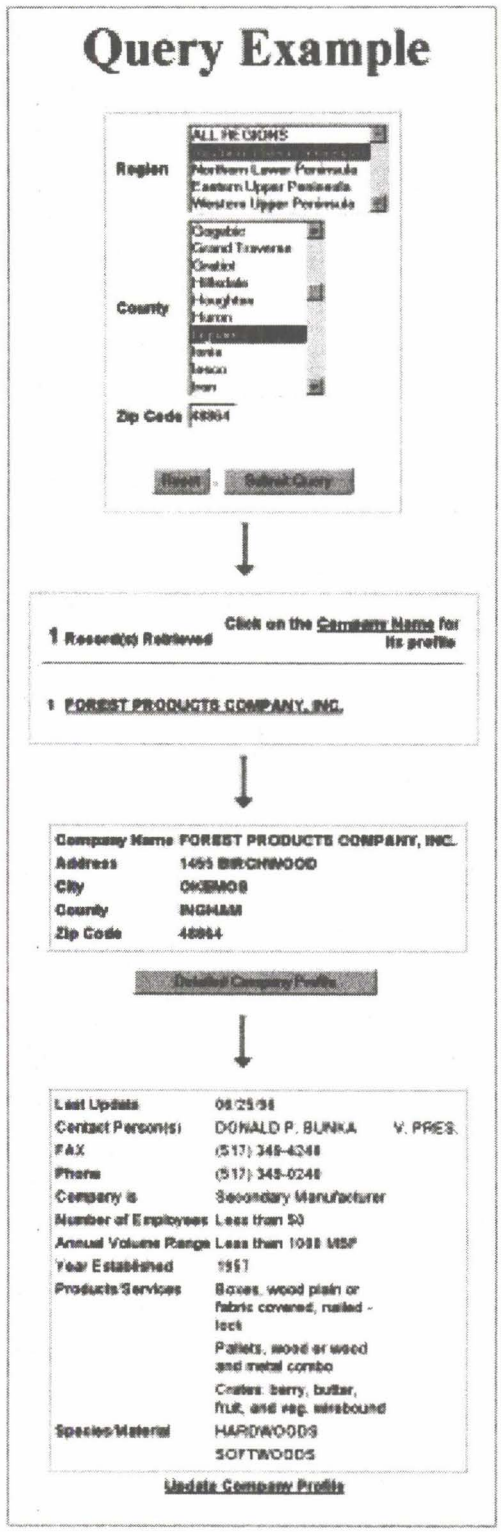

Figure 5.—*Query example.*

FOREST SCENARIO STUDIES FOR EUROPEAN FORESTS

G.J. Nabuurs and R. Päivinen[1]

ABSTRACT.—European forests, amounting to 150 million ha, are scattered over 30 countries, many of which only have a small forest area. These countries are increasingly regarding their forest management and policy in an international context in which many issues (e.g., nature oriented forest management and likely effects of climate change) are evolving rapidly. Because of the diversity in forest scenario analyses methods used in European countries, the European Forest Institute started a study on a new forest resource projection approach for all countries with one harmonized methodology. For this baseline-study, an existing model was used and applied to a complete new data set. After this baseline projection, which will be completed in the summer of 1997, the model will be evaluated and further developed to better meet the present day issues in European forestry.

INTRODUCTION

European forests, amounting to 150 million ha (excl. former Soviet Union), are scattered over 30 countries, many of which only have a small forest area. These countries are increasingly regarding their forest management and policy in an international context (e.g., they regard their wood products market as part of their involvement in international trade). Also, the ability of the forest to respond to environmental changes like acidification or climate change which may be contributing to the steadily declining forest health in Europe is limited. Another concrete aspect threatening the sustainability of European forests is the increasing impact of forest fires in the Mediterranean area. This influence on the health of forest ecosystems is mainly seen as a problem which originates outside the forest sector. Further, views of society on the role of forests and forest management are in flux. While in the past, forests mainly fulfilled the goal of wood production, they now have to fulfill an increasing number of new types of demands.

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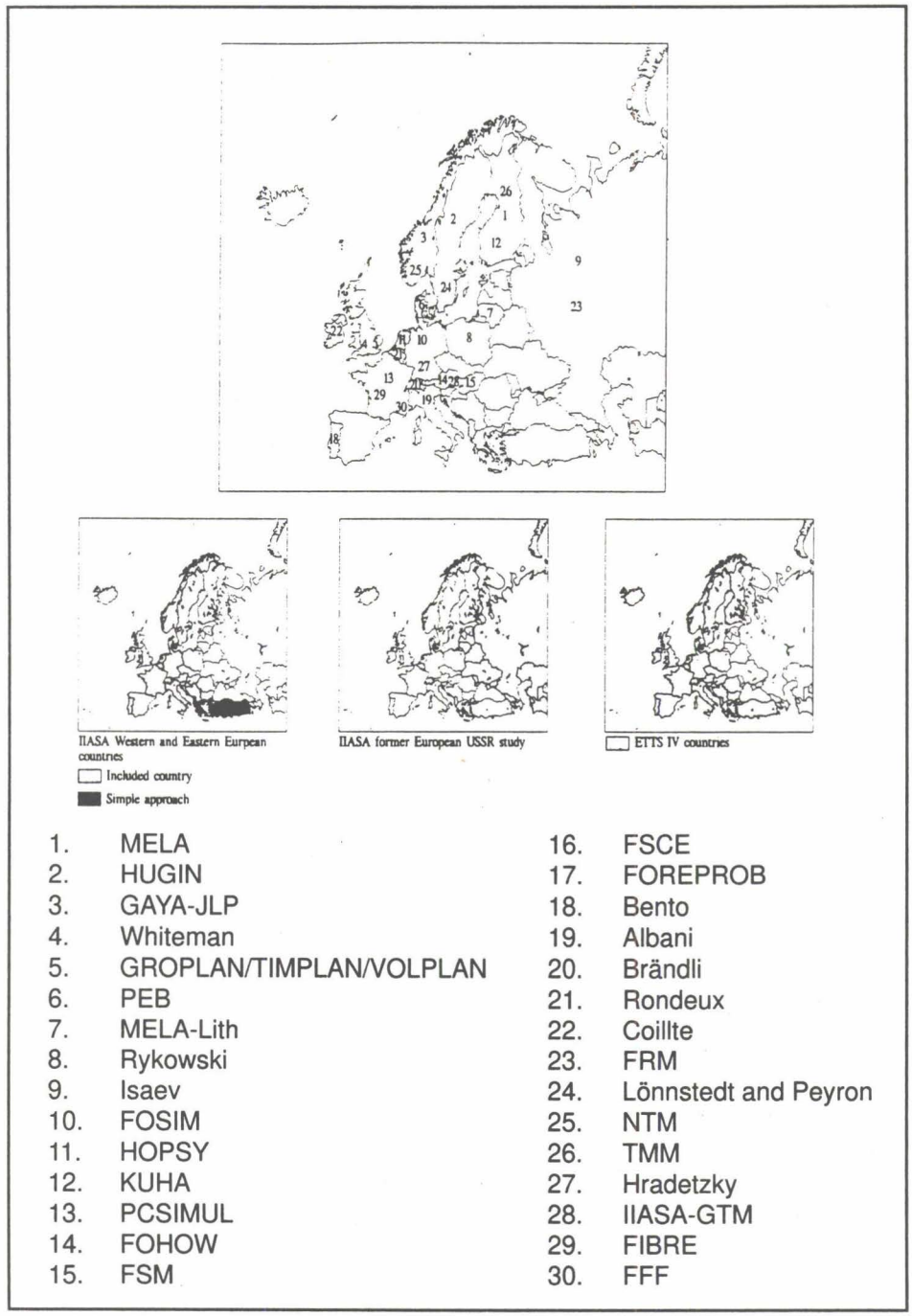
At the European level, sustainable forest management has received ample attention through the UNCED conference and the European Ministerial Conferences on the Protection of Forests in Europe. This trend towards multifunctional natural resource management is not only taking place at the international policy level, but also at the practical forest management level within countries in Europe. The criteria and indicators which are being identified (e.g., via the Helsinki process) will have to be applicable at the practical forest management level also.

This paper identifies a type of tool which may help in gaining insight in the future development of European forests as it relates to the issues described above. The advantage of this type of tool is that it applies a standardized methodology to all countries. As is described below, that's a big advantage in comparison to the national level studies which have been carried out in the past.

NATIONAL LEVEL LARGE-SCALE-FORESTRY-SCENARIO-MODELS IN EUROPE

In the 1960's and 1970's, several European countries have developed a forestry scenario analysis tool for their national forest area (MELA for Finland, FOSIM for Germany, HUGIN for Sweden, HOPSY for The Netherlands) (Englert and Sasse 1994, Hinssen 1994, Lundström and Söderberg 1996, Siitonen and Nuutinen 1996) (fig. 1). These are usually rather traditional forestry analysis tools which focus on the timber value of the forest, are designed for a specific scale of analysis, and involve a high level of aggregation. Each national model has also been designed to deal with circumstances and forestry related problems specific to a particular country. Where these tools are still under development, there is a trend towards greater complexity, a higher level



1. MELA
2. HUGIN
3. GAYA-JLP
4. Whiteman
5. GROPLAN/TIMPLAN/VOLPLAN
6. PEB
7. MELA-Lith
8. Rykowski
9. Isaev
10. FOSIM
11. HOPSY
12. KUHA
13. PCSIMUL
14. FOHOW
15. FSM
16. FSCE
17. FOREPROB
18. Bento
19. Albani
20. Brändli
21. Rondeux
22. Coillte
23. FRM
24. Lönnstedt and Peyron
25. NTM
26. TMM
27. Hradetzky
28. IIASA-GTM
29. FIBRE
30. FFF

Figure 1.—*Continental map showing the distribution of the large scale scenario models in Europe. When a model does not have an official acronym, the present contact person's name is given in sentence case.*

of detail, spatial analysis and multiple-use analysis (Nabuurs and Päivinen 1996). Developers usually regard their models as having the potential to incorporate the effects of environmental change. There is also a trend of convergence between forest sector models and forestry scenario models.

Harmonization of these models at the European level, would not only be desirable in terms of output comparison, but also because most European countries have a limited forest area with little influence on the wood markets. Harmonization at the European level would make it possible to study their influence on the wood market and vice versa. Such harmonized results would make it possible to work towards European level scenario studies, based on the available national expertise. Harmonization at the European level would also make it possible to study, for example, wood production shifts between countries when one country decides to set aside forests for nature.

A EUROPEAN-SCALE FORESTRY SCENARIO MODEL

A baseline study designed to generate a forest resource projection for Europe has been underway since 1995 at the European Forest Institute. The approach has been to use existing models which could be relatively easily applied to the most recent data. Experience with these models could form the basis for evolution improvements in the future while at the same time guiding the assessment of indicators of sustainable forest management.

A model developed in the early 1980's by Sallnäs (and used for the IIASA forest study for European forests) (Nilsson *et al.* 1992) was selected for even-aged forests. This large scale, aspatial scenario model generates projections of growing stock and timber harvest volumes over time by country, species group, and age. It requires several variables to characterize the forest types by country, and a working knowledge of current forest management regimes. At present, the model can simulate varying aspects of managing existing forests and the policy implications of newly afforested land. Furthermore, the growth of the forest can be adjusted according to assumed effects of forest decline, or other phenomena which influence forest growth (Spiecker *et al.* 1996). The EFI baseline study is based on a new data set compiled from information provided by all national forest inventory institutes in Europe.

In the Sallnäs model, a matrix is defined by 10 intervals for the volume and 6-15 intervals for age. The forest state is then depicted by the matrix generator as an area distribution over this matrix. Dynamics of volume increment are expressed as transitions of areas between specific fixed states in the matrix.

The model contains some variables and scenario options which provide indirect information about nature values. These include age class distribution, standing volume, and degree of indigenous species.

For uneven-aged forests in Spain, France, and Italy, a model based on stem number per diameter class is used (Guo *et al.* In press). This model simulates forest resource development based on transition rates between diameter classes.

In the baseline study, these models will be used for the following scenarios:

1. A baseline scenario using the latest data,
2. A maximum sustainable timber production scenario,
3. A nature conservation scenario.

SOME RESULTS

Some provisional results offer insight into the kinds of analysis which are possible using this model. As of this writing, European level scenario outputs are not yet available. The model produces output on variables such as distribution of forest area over volume and age classes at the national level and by tree species during the simulation period, mean volume development during the simulation, mean age development during the simulation at the tree species level, and the actual harvest from thinning and final felling at the national level and by region and tree species. The following figures present some examples of these output variables.

Figure 2 shows the development of the total forest area of a country under a scenario in which the current harvesting levels are maintained as they were in the initial situation. In essence, this tests a scenario of 'business as usual' for long-term sustainability. In this case, the rather young forest in the initial situation develops a larger area with rather high standing volumes. Also, by 2090 quite a large area exists of recently regenerated forest. Possible over-harvesting would have shown up in this figure as a decrease in the forest area in the middle age and middle volume classes. Also, the model stops the actual harvest when there is no forest area available in the age classes and volume classes where, in principle, final felling can occur. So, a decrease in actual harvest can also indicate harvesting levels which reach their maximum sustainable level (fig. 3).

Figures 3 and 4 show some variables which indicate whether or not a certain harvesting level can be sustained. The harvesting levels have been set too high in this scenario and the output shows that the model can no longer find the required thinning volumes as of 2025. Since thinning was incorporated in the model as a percentage of the increment per age class, a reasonable

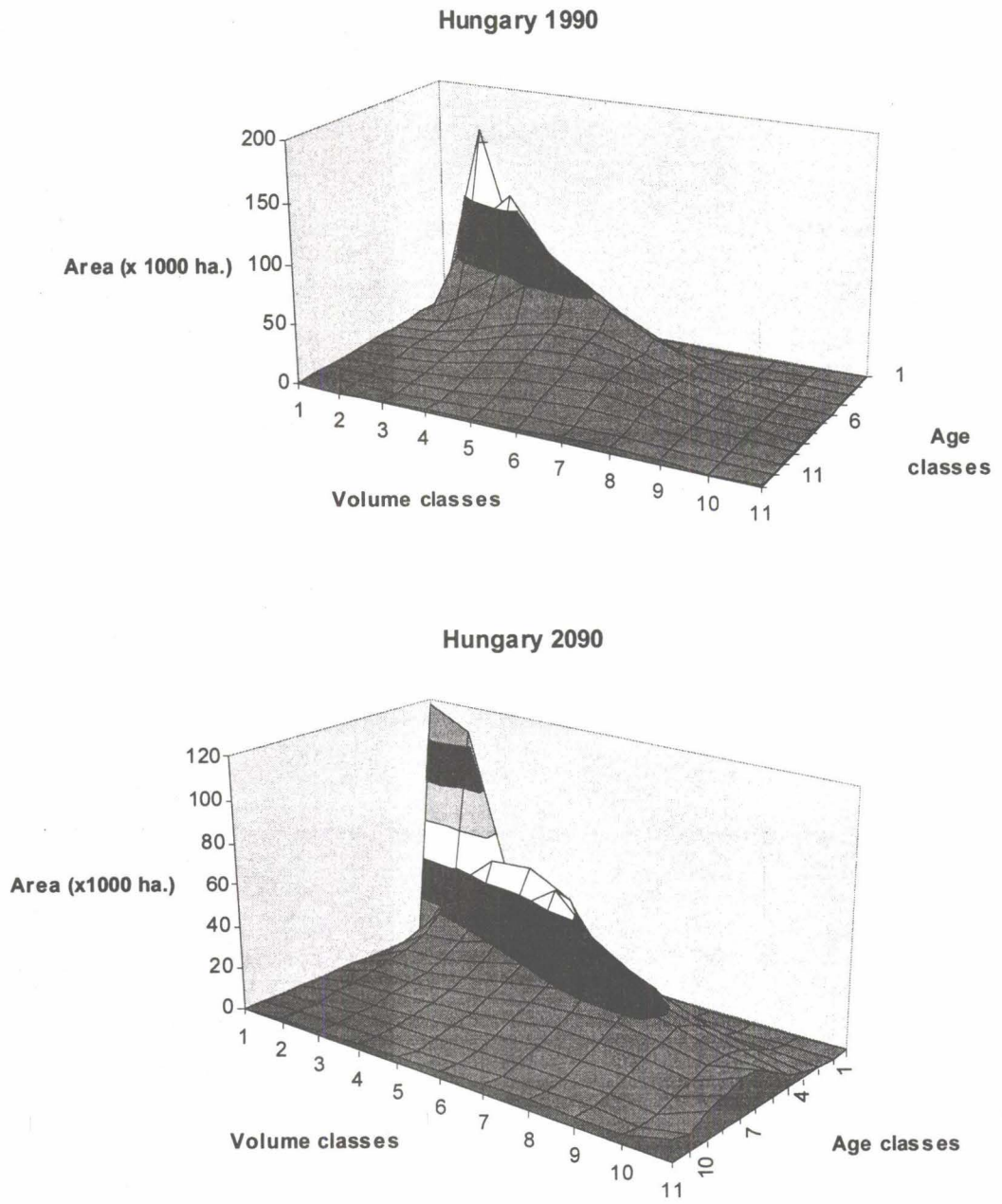


Figure 2.—*Distribution of the total forest area of Hungary (1,675,000 ha) over volume and age classes at the beginning 1990) and end (2090) of the simulation.*

interpretation would be that the increment is too low to sustain this thinning level. The final felling seems to be no problem. Because the model cannot find the required thinning volumes and therefore reduces the thinning, the average standing volumes are maintained reasonably well (fig. 4).

Figure 5 shows a characteristic feature which can be seen in many European countries in the future. Due to the aging of the forest, the increase in the average growing stock per hectare levels off, and the net annual increment steadily declines, ultimately influencing the maximum level of sustainable production.

DISCUSSION

These model results demonstrate only few of the variables that can be tested. The model produces output on: (1) variables as a distribution of forest area over volume and age classes at the national level and according to tree species, (2) mean volume development during the simulation, (3) mean age development during the simulation at the national level and according to tree species, and (4) the actual harvest from thinning and final felling at the national level and according to region and tree species. Especially because the model requires harmonized input for every country and because the

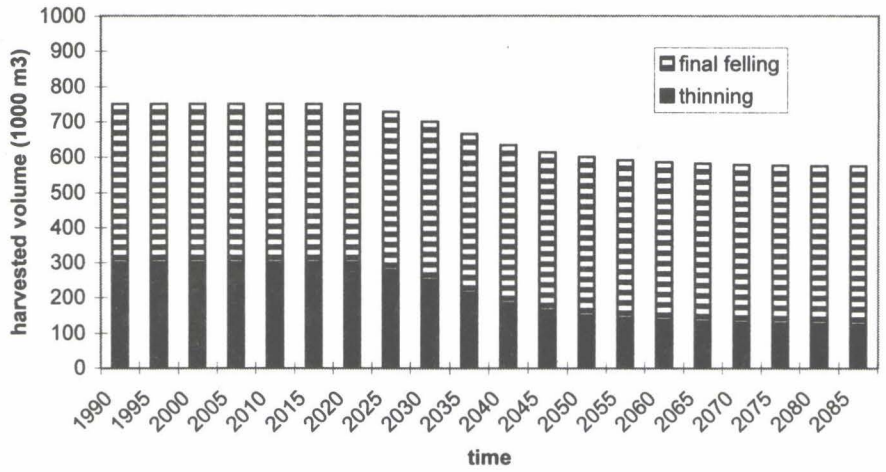


Figure 3.—*Harvest volume from thinning and final felling for a country under a scenario of over-harvesting.*

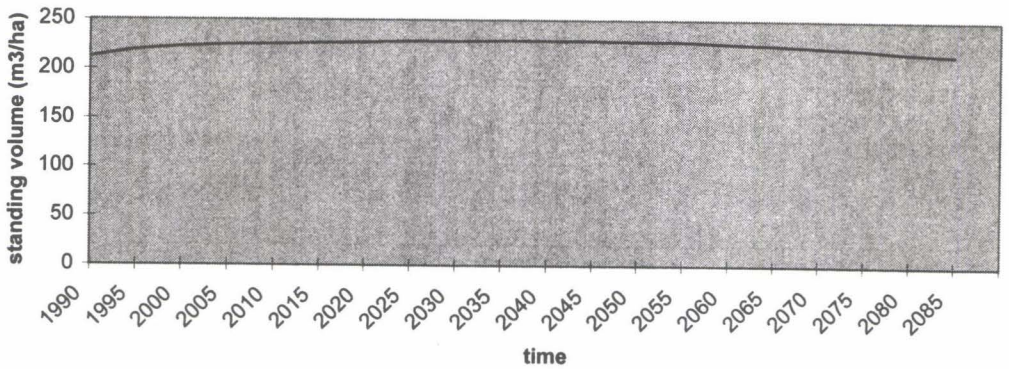


Figure 4.—*Development of the average standing volume of hardwood forest under the same scenario of over-harvesting as in figure 3.*

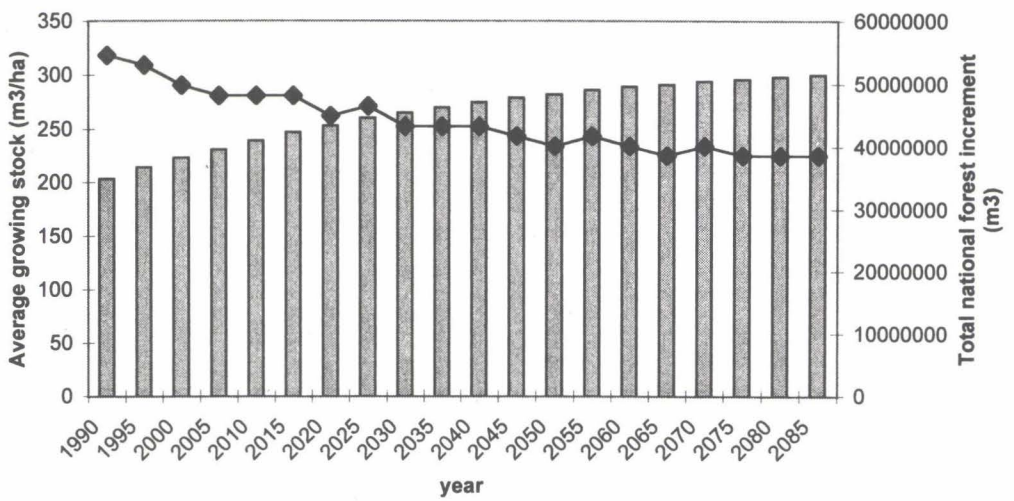


Figure 5.—*Maturing of the forest in a European country shown by the trajectories of growing stock (bars) and increment (marker and line) during the period of simulation.*

calculation methodology is harmonized, the results could easily serve as a tool for assessing some of the indicators for sustainable forest management as mentioned above. After the baseline study has been completed, the model could be further developed for studies like:

- linking this forestry model to forest sector analyses;
- incorporating GIS approaches which enable visualization of the effects of regional differences in management;
- incorporation of the effects of possible climate change based on detailed knowledge of those effects;
- related to the previous study, the model could also serve as a basis for a future European forest sector carbon balance; and
- improving the ability to take into account nature oriented forest management and natural dynamics.

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This international symposium included presentations by representatives from government, academic, and private institutions. Topics covered management objectives; information systems: modeling, optimization, simulation, and decision support techniques; spatial methods; timber supply; and economic and operational analyses.

KEY WORDS: Simulation, optimization, modeling, spatial analysis, heuristics, systems analysis.

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